A WIDE BAND FREQUENCY-ADJUSTABLE PIEZOELECTRIC ENERGY HARVESTER: AN EXPERIMENTAL STUDY

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Piezoelectric energy harvester has become a new powering choice for small electronic device. Due to its piezoelectric effect, electric energy can be obtained from ambient vibrations. This thesis is intending to build a frequency-adjustable piezoelectric energy harvester system. The system is structured with two piezoelectric bimorph beams, which are connected to each other by a spring. The feasibility of the frequency-adjustable piezoelectric energy harvester has been proved by investigating effects of the spring, loading mass and impedance on the operation frequencies.
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By

Pohua Lee
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGEMENTS</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES AND FIGURES</td>
<td>v</td>
</tr>
<tr>
<td>CHAPTER 1  INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER 2  LITERATURE REVIEW</td>
<td>3</td>
</tr>
<tr>
<td>CHAPTER 3  THEORETICAL BACKGROUND OF THE PIEZOELECTRIC ENERGY HARVESTER</td>
<td>5</td>
</tr>
<tr>
<td>CHAPTER 4  EXPERIMENT METHODOLOGY</td>
<td>11</td>
</tr>
<tr>
<td>4.1. Experiment Preparation</td>
<td>11</td>
</tr>
<tr>
<td>4.2. Measurement Procedure</td>
<td>17</td>
</tr>
<tr>
<td>CHAPTER 5  EXPERIMENT RESULT</td>
<td>19</td>
</tr>
<tr>
<td>5.1. Influence of Masses on the Operation Frequency of the Energy Harvester</td>
<td>19</td>
</tr>
<tr>
<td>5.2. Effect of Spring on the Operation Frequency of the Energy Harvester</td>
<td>21</td>
</tr>
<tr>
<td>5.3. Effect of Impedance on the Operation Frequency of the Energy Harvester</td>
<td>23</td>
</tr>
<tr>
<td>CHAPTER 6  CONCLUSION AND FUTURE RESEARCH</td>
<td>25</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>26</td>
</tr>
</tbody>
</table>
# LIST OF TABLES AND FIGURES

## Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Types of Spring and Mass</td>
<td>18</td>
</tr>
<tr>
<td>12</td>
<td>Test results of spring constant 10.51 N/m</td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>Test results of spring constant 208.40 N/m</td>
<td>21</td>
</tr>
<tr>
<td>14</td>
<td>Test results of mass type 1</td>
<td>22</td>
</tr>
<tr>
<td>15</td>
<td>Test results of mass type 2</td>
<td>22</td>
</tr>
<tr>
<td>16</td>
<td>Test results of mass type 3</td>
<td>23</td>
</tr>
<tr>
<td>17</td>
<td>The influence of loaded impedance on the resonant frequency (beam (1) =2.137 g, beam (2) =2.342 g, spring rate=10.51 N/m)</td>
<td>24</td>
</tr>
<tr>
<td>18</td>
<td>The influence of loaded impedance on the resonant frequency (beam (1) =2.137 g, beam (2) =2.342 g, spring rate=26.27 N/m)</td>
<td>24</td>
</tr>
</tbody>
</table>

## Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic of piezoelectric bimorph beam and series circuit connection</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Picture of the PZT-5X piezoelectric bimorph beam. (Picture from APC international, Ltd. Website)</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Schematic of the fixture and sample</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Schematic of the dimension of connecting cube</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Connection of spring, bimorph beam and mass</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>Schematic of experiment process</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>Shaker and piezoelectric bimorph structure</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Power supply amplifier of shaker</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>Function generator, multi-meter and oscilloscope</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>The control panel and the monitor graph of the LabVIEW VI</td>
<td>17</td>
</tr>
<tr>
<td>11</td>
<td>Test results of spring constant 10.51 N/m</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>Test results of spring constant 26.27 N/m</td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>Test results of spring constant 208.40 N/m</td>
<td>21</td>
</tr>
<tr>
<td>14</td>
<td>Test results of mass type 1</td>
<td>22</td>
</tr>
<tr>
<td>15</td>
<td>Test results of mass type 2</td>
<td>22</td>
</tr>
<tr>
<td>16</td>
<td>Test results of mass type 3</td>
<td>23</td>
</tr>
<tr>
<td>17</td>
<td>The influence of loaded impedance on the resonant frequency (beam (1) =2.137 g, beam (2) =2.342 g, spring rate=10.51 N/m)</td>
<td>24</td>
</tr>
<tr>
<td>18</td>
<td>The influence of loaded impedance on the resonant frequency (beam (1) =2.137 g, beam (2) =2.342 g, spring rate=26.27 N/m)</td>
<td>24</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

As the technology has advanced, more and more small electric devices and wireless electronics are emerged. Many of those devices require different powering sources than the traditional wired power or battery. In the meantime, due to the fast technology innovation, the improved performance of an electronic device increased the power usage. However, the growth of the battery technology has not caught up with the growth of the power usage. More frequent battery changing became an issue or even an impossible task to be finished. Therefore, in order to overcome these difficulties, researchers found out that obtaining electrical energy from the ambient energy sources around the device may be a solution. Methods have been proposed such as, electromagnetic induction [1], electrostatic generation [2], dielectric elastomers [3], and piezoelectric materials [4-7]. Among all these methods, energy harvesting using piezoelectric materials seems to be the most promising one, because they could convert mechanical energy into electrical energy directly and they are also easy for system integration [4].

A piezoelectric material is named from its piezoelectric effect—a voltage (potential difference) will be developed across its faces when the piezoelectric material is compressed, or it will change its shape physically when applying an external electric field on it [8-12]. The piezoelectric material can generate power in a narrow frequency range, and generate the largest power at a specific resonant frequency. However, if the energy harvester system is located in areas or places that may not provide a stable frequency or even could not reach the resonant frequency, the performance will be down-graded [13-14]. Therefore, making the operating frequency wider and self-adjustable is a possible way to improve the performance of the piezoelectric energy harvester.
In this thesis, an initial attempt of building a frequency-adjustable piezoelectric energy harvester system is made by using a spring to connect two piezoelectric bimorph beams on a vibrating source, and adding masses at the end of each beam. With this structure, operating in the wide-band frequency range and making the resonant frequency adjustable will be achieved [15]. Experimental data would be generated by using three different springs, and each of them would run the test in three types of mass loading and two output impedance. Therefore, by analyzing the data, the feasibility of a frequency self-adjustable piezoelectric energy harvester would be able to be proved.
CHAPTER 2

LITERATURE REVIEW

Yang et al. [15] introduced an exact analytical solution to a two piezoelectric bimorph beam structure. Based on the numerical results of the analytical solution, a proper design is proposed which can tune the resonances frequency of each beam. Therefore, by controlling the mass attached to each end of beam and the spring constant connected, a wide-band piezoelectric power harvester can be designed.

Guyomar et al. [16] compared several piezoelectric energy harvesting methods, and provided the detailed energy flow explanations and the mechanisms for each method. They also considered the pyroelectric effect. This article gives a better understanding of the mechanisms of energy harvesting process for ambient vibration and thermal energy harvesting.

Hu et al. [17] studied a piezoelectric power harvester with adjustable frequency through axial preloads. They illustrated a simplified framework and the mechanism of the piezoelectric harvester. The computational results show that the resonant frequency of a piezoelectric bimorph is adjustable by adding proper axial preload.

Jiang et al. [18-19] studied the effects of both central-attached and end-attached mass energy harvester structure. They derived a numerical result, and suggested that the performance of the energy harvester can be more efficient by adjusting its physical and geometrical parameters of the scavenging structure.

Taylor et al. [20] presented an energy harvester system which would be able to harvest energy from ocean/river. In the system, it included not only the energy harvester device but also devices of the water flow detection and data transmitting. All these devices are powered by its
energy harvesting part. This gives a good example of a self-powered device which may be working in a place that could not use wired power or unable to change the battery.
CHAPTER 3
THEORETICAL BACKGROUND OF THE PIEZOELECTRIC ENERGY HARVESTER

The piezoelectric bimorph model is shown schematically in Fig. 1.

![Figure 1: Schematic of piezoelectric bimorph beam and series circuit connection.](image)

The principle of the energy harvesting system can be explained by 3-D piezoelectric theory. Since the experiment is in flexural vibration in the $x_3$ direction, a typical beam the flexural motion $u_3$ is governed by [5]

$$-Du_{3,111} = m\ddot{u}_3,$$

(1)

where $D$ is the beam bending constant and $m$ is the mass per unit length of the beam [5]

$$D = \left\{Ec^3 + \frac{2}{3}s_{11}^{-1}\{(c + h)^3 - c^3\}\right\}b,$$

(2)

$$m = \rho 2cb + 2\rho' hb,$$

(3)
where $E$ is the Young’s modulus of the isotropic elastic layer, $C_{ij}$ is the elastic compliance at constant electric field of the piezoelectric layers [5] [9]. and $\rho$ are the mass densities of the elastic and piezoelectric layers. The beam bending moment $M$ is also given [5]

$$M = \int x_3 T_1 dx_2 dx_3 = -Du_{3,11} + s_{11}^{-1} d_{31} V 2G,$$  

where $V$ is the voltage across each of the two piezoelectric layers, $d_{31}$ is the relevant piezoelectric constant, and

$$G = \left(c + \frac{h}{2}\right) hb$$

where $G$ is the first moment of the cross-sectional area of one of the ceramic layers about the axis. In addition, the transverse shear force in the beam is related to the bending moment and the flexural displacement [5]

$$N = \int T_{13} dx_2 dx_3 = M_{,1} = -Du_{3,111}.$$  

At the left end of the cantilevered beam, the boundary conditions are

$$u_3(0,t) = A \exp(i\omega t),$$

$$u_{3,1}(0,t) = 0.$$  

At the right end, there is no bending moment:

$$M(L,t) = 0.$$  

The electric charge on the top electrode at [5]

$$Q_e = -b \int_0^L D_3(X_3 = c + h) dx_1$$

$$= b \left\{ s_{11}^{-1} d_{31} (c + h) \left[ u_{3,1}(L,t) - u_{3,1}(0,t) \right] + \bar{\varepsilon}_{33} \frac{V}{h} L \right\},$$

where

$$\bar{\varepsilon}_{33} = \varepsilon_{33} (1 - k_{31}^2), \quad k_{31}^2 = \frac{d_{31}^2}{(\varepsilon_{33}s_{11})},$$

and is the electric permittivity at constant [5].
\[ I = -\dot{Q}_e \]  

Equation (11) is the current flowing out of the electrode for each of the two bimorph beams. Since the two bimorph are parallel connected, and the motion is time-harmonic, the output voltage and current,

\[ 2[I^{(1)} + I^{(2)}] = \frac{V}{Z_L}, \]  

where \( Z_L \) is the complex impedance of the output circuit. The mass at the right end of the upper beam will be

\[ -N^{(1)}(L, t) - K[u_3^{(1)}(L, t) - u_3^{(2)}(L, t)] = m_0^{(1)}\ddot{u}_3^{(1)}(L, t). \]  

For the mass at the right end of the lower beam,

\[ -N^{(2)}(L, t) - K[u_3^{(1)}(L, t) - u_3^{(2)}(L, t)] = m_0^{(2)}\ddot{u}_3^{(2)}(L, t) ..... \]  

Under harmonic motions, the first and the second beam, a complex notation is used

\[ \{u_3(x), V, Q_e, I\} = \text{Re}\{U(x), V, Q_e, I\exp(i\omega t)\} \]  

Thus Equation (1) becomes

\[ -DU_{1111} = -\omega^{w}mU, \quad 0 < x_1 < L. \]  

The general solution to (16) can be written as [5] [9].

\[ U = B_1 \sin \alpha x_1 + B_2 \cos \alpha x_1 + B_3 \sinh \alpha x_1 + B_4 \cosh \alpha x_1, \]  

where \( B_1, B_2, B_3, B_4 \) are undetermined constants, and

\[ \alpha = \left(\frac{m}{D}\omega^2\right)^{1/4}. \]  

Substituting of (17) into (9) and (11), the complex current is given

\[ \bar{I} = -i\omega b \left\{ \frac{d_{11}}{\lambda_{11}} (c + h) [B_1 \alpha \cos \alpha L - B_2 \alpha \sin \alpha L + B_3 \alpha \cosh \alpha L + B_4 \alpha \sinh \alpha L] + \bar{e}_{33} \frac{V}{h} L \right\}. \]
For the boundary condition with superscripts (1) and (2) for each beam

\[ U^{(1)}(0) = A, \]
\[ U^{(1)}_{,1}(0) = 0, \]
\[ -D^{(1)} U^{(1)}_{,11}(L) + \frac{d^{(1)}_{s11} \bar{V}}{s_{11}^2 h^4} 2G^{(1)} = 0, \]  
(20)
\[ U^{(2)}(0) = A, \]
\[ U^{(2)}_{,1}(0) = 0, \]
\[ -D^{(2)} U^{(2)}_{,11}(L) + \frac{d^{(2)}_{s11} \bar{V}}{s_{11}^2 h^2} 2G^{(2)} = 0, \]

Substituting (17) and (19) into (20), (13), (14), and the circuit equation (12)

\[ B_2^{(1)} + B_4^{(1)} = A, \]
\[ B_1^{(1)} \alpha + B_3^{(1)} \alpha = 0, \]
\[ -D \left(-B_1^{(1)} \alpha^2 \sin \alpha L - B_2^{(1)} \alpha^2 \cos \alpha L + B_3^{(1)} \alpha^2 \sinh \alpha L + B_4^{(1)} \alpha^2 \cosh \alpha L \right) s_{11}^{-1} d_{31} \frac{\bar{V}}{h} 2G = 0 \]
\[ B_2^{(2)} + B_4^{(2)} = A, \]
\[ B_1^{(2)} \alpha + B_3^{(2)} \alpha = 0, \]
\[ -D \left(-B_1^{(2)} \alpha^2 \sin \alpha L - B_2^{(2)} \alpha^2 \cos \alpha L + B_3^{(2)} \alpha^2 \sinh \alpha L + B_4^{(2)} \alpha^2 \cosh \alpha L \right) s_{11}^{-1} d_{31} \frac{\bar{V}}{h} 2G = 0 \]
\[ D \left(-B_1^{(1)} \alpha^3 \cos \alpha L - B_2^{(1)} \alpha^3 \sin \alpha L + B_3^{(1)} \alpha^3 \cos \alpha L + B_4^{(1)} \alpha^3 \sinh \alpha L \right) \]
\[ + K \left(B_1^{(2)} \sin \alpha L + B_2^{(2)} \cos \alpha L + B_3^{(2)} \sinh \alpha L + B_4^{(2)} \cosh \alpha L \right) + \left(m_0 \omega^2 \right) \]
\[ - K \left(B_1^{(1)} \sin \alpha L + B_2^{(1)} \cos \alpha L + B_3^{(1)} \sinh \alpha L + B_4^{(1)} \cosh \alpha L \right) = 0 \]
\[
\begin{align*}
& D \left( -B_1^{(2)} \alpha^3 \cos \alpha L + B_2^{(2)} \alpha^3 \sin \alpha L + B_3^{(2)} \alpha^3 \cos \alpha L + B_4^{(2)} \alpha^3 \sinh \alpha L \right) \\
& \quad + K \left( B_1^{(1)} \sin \alpha L + B_2^{(1)} \cos \alpha L + B_3^{(1)} \sin \alpha L + B_4^{(1)} \cosh \alpha L \right) + (m_0^{(2)} \omega^2 \\
& \quad - K \right) \left( B_1^{(2)} \sin \alpha L + B_2^{(2)} \cos \alpha L + B_3^{(2)} \sin \alpha L + B_4^{(2)} \cosh \alpha L \right) = 0 \\
& \quad - 2i\omega b \left\{ \frac{d_{31}}{s_{11}} (c + h) \left[ (B_1^{(1)} + B_1^{(2)}) \alpha \cos \alpha L - (B_2^{(1)} + B_2^{(2)}) \alpha \sin \alpha L + \\
& \quad \left( B_3^{(1)} + B_3^{(2)} \right) \alpha \cosh \alpha L + \left( B_4^{(1)} + B_4^{(2)} \right) \alpha \sinh \alpha L \right] + 2\varepsilon_{33} \frac{\bar{V}}{L} \right\} = \frac{\bar{V}}{Z_L} \tag{21}
\end{align*}
\]

With the above nine equations for \( \text{to, to, and } \), the output power is given by [5]
\[
P = \frac{1}{2} \left[ (\bar{I}^{(1)} + \bar{I}^{(2)}) \bar{V}^* + (\bar{I}^{(1)} + \bar{I}^{(2)})^* \bar{V} \right], \tag{22}
\]
where an asterisk represents complex conjugate. The power density, as the output power per unit volume, in a miniaturized power harvester, is shown [5]
\[
p = \frac{P}{2b(2c+2h)L}. \tag{23}
\]

The resonant frequency of a single bimorph beam can be calculated by the following equations [21]
\[
f_n = \frac{v_n^2}{2\pi} \sqrt{\frac{0.236w_pE_0(l-l_m/2)^3}{0.236m_p} + \Delta m l^3(l-l_m/2)}, \tag{24}
\]
\[
E_0 = \frac{2E_p t_p^3}{3} + E_p t_{sh} t_p^2 + \frac{E_p t_{sh}^2 t_p}{2} + \frac{t_{sh}^3 E_{sh}}{12}, \tag{25}
\]
\[
m = 2\rho_p t_p + \rho_{sh} t_{sh}, \tag{26}
\]
\[
\Delta m = \rho_m l_m w_m h_m. \tag{27}
\]

where \( l \) is the total length of the cantilever, \( l_m \) the length of the loading mass, \( m \) is the mass of the bimorph beam structure without the loading mass, \( w \) the width of the bimorph beam, \( \rho \), and \( E \), are the density, the thickness and the Young’s modulus of the piezoelectric material respectively. \( \rho \), and \( \rho_{sh} \), are the density, the thickness and the Young’s modulus of the center coupling metal.
respectively, is a constant, is the mode vibration, the loading mass, , and , respectively represent the density, the width, and the height of the loading mass.

According to equation (24), increasing of the weight of the loading mass will reduce the resonant frequency. The equations (12), (18) and (21) indicate that increasing the weight of the loading mass can also increase the voltage output. From equation (12), increasing the impedance of the output circuit will increase the output power. In addition, from the above equations, the resonant frequency of the energy harvester system can be reduced by connecting a spring between the two beams [5]. Therefore, the above lay the foundation for the following experiment. With proper applied boundary condition, the power output of the energy harvester would be derived.
CHAPTER 4

EXPERIMENT METHODOLOGY

4.1. Experiment Preparation

4.1.1. Samples

The piezoelectric bimorph beams used in this research are PZT-5X purchased from the APC International, Ltd, showed on the left side of the Fig. 2, which is made by lead zirconate titanate and 60x20x0.69 mm for the length-width-thickness. The resonant frequency of the sample is 60 Hz.

![Figure 2: Picture of the PZT-5X piezoelectric bimorph beam. (Picture from APC international, Ltd. Website).](image)

4.1.2. Fixture

CAD software-SolidWorks is used to design a structure showed in Fig. 3, which is used to hold two piezoelectric bimorph beams. The structure, also called “fixture”, is connected to a shaker (VG-100).
By using two threaded cylinder bars, the top and bottom fixtures are able to adjust the related distance. At the end of each bimorph beams, the two bimorph beams are connected through a tension spring through two connecting units showed in Fig. 4. A small plastic screw, which is only 0.043g, is used to tight the bimorph beam and the connecting unit on each bimorph beams. In addition, on the end of each bimorph beams, another small plastic screw is used to serve as the base of the mass. The loading mass can be adjusted by adding small steel nuts on the plastic screw. The connection of the spring, bimorph beam, and mass is shown in Fig. 5. The fixture is then fixed on a shaker.

A voltmeter (HP 33401A) is use to determine the power output. The circuit is connected in a series circuit connection shown in Fig. 1. The voltmeter is connected to an oscilloscope (TDS3054C), and then connected to the computer.

4.1.3. Equipment and Facility

In addition to the sample and the fixture, several devices are used in this experiment, which are showed in Fig. 6:

• Shaker (VG-100) is used to provide a vertical vibration. Fig. 7 shows how the shaker and the fixture are connected.

• Power supply amplifier (Techron7541), showed in Fig. 8, is used to power and drive the shaker. By connecting to a function generator, the amplifier could drive the shaker at a desired frequency.

• Voltage meter (HP33401A), showed in Fig. 9, is used to read the voltage output from the experiment. The voltage meter is connected to a channel on the oscilloscope and is connected to the computer by GPIB cable.

• Function Generator (HP33120A), showed in Fig. 9, is used to output a signal to the
power supply amplifier of the shaker. The function generator is also connected to a channel on the oscilloscope and is connected to the computer by GPIB cable.

- Oscilloscope (TDS3054C), showed in Fig. 9, is used to be a communication center between the computer and other devices.

- LabVIEW software, showed in Fig. 10, in the computer is the controlling center of the whole experiment. It is used to assign the exciting frequency to the function generator, to set the reading type of the voltage meter, and to record the readings from the oscilloscope.

Figure 3: Schematic of the fixture and sample.
Figure 4: Schematic of the dimension of connecting cube.

Figure 5: Connection of spring, bimorph beam and mass.
Figure 6: Schematic of experiment process.

Figure 7: Shaker and piezoelectric bimorph structure.
Figure 8: Power supply amplifier of shaker.

Figure 9: Function generator, multi-meter and oscilloscope.
4.2. Measurement Procedure

The whole experiment is performed at room temperature. A LabVIEW VI, showed in Fig. 10, is designed to control and monitor the experiment process, and to record the experiment data. In the VI, starting frequency, ending frequency and a frequency increment can be set in the section of function generator to drive the mechanical shaker. By connecting the Optical displacement detector and voltmeter to the oscilloscope, the VI could also monitor and record the designed channels on the oscilloscope. The schematic of Experiment process is showed in Fig. 5. The arrows in the figure indicate the signal direction.

Figure 10: The control panel and the monitor graph of the LabVIEW VI.

The previous studies [7] [9] has indicated that resonant frequency can be adjusted by a proper axial load. Other than that, Yang et al. [5] has also indicated that resonant frequency can also be adjusted by connecting two bimorph beams with spring. Therefore, three types of spring and three types of mass setting are used in this research, showed as Table 1. In the experiment, each spring is tested in three different mass types. For example, S1M1 is one test; S1M2 and S1M3 are two other tests.
The function generator is set in the LabVIEW VI from 5 to 45 Hz for the frequency range, the frequency increment is 0.1 Hz, and the waiting time between each step is 0.3 second. After one test is done, the data can be saved by the LabVIEW VI.

Table 1: Types of Spring and Mass

<table>
<thead>
<tr>
<th>Spring Stiffness/Constant (manufacture value)</th>
<th>Upper Beam</th>
<th>Lower Beam</th>
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<tbody>
<tr>
<td>S1</td>
<td>10.51 N/m</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>26.27 N/m</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>208.40 N/m</td>
<td></td>
</tr>
<tr>
<td>Mass Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>2.137 g</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>2.342 g</td>
<td>2.342 g</td>
</tr>
<tr>
<td>M3</td>
<td>2.666 g</td>
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</tbody>
</table>
5.1. Influence of Masses on the Operation Frequency of the Energy Harvester

In Figs. 10, 11 and 12, each spring is respectively tested with three different mass types: M1, M2, and M3, and the effect of the loading mass can be determined.

In Fig. 11, a spring with spring constant 10.51 is used in the experiment. The blue solid line is loaded with M1 mass type, the green dotted line is loaded with M2 mass type, and the red dashdot line is loaded with M3 mass type. It clearly shows that the resonant frequency between three mass types has been lowered a few Hz. The difference between blue and green line is less than 0.5 Hz, and the difference between green and red line is about 1 Hz. These Phenomena may be explained by equation (24). In addition, the power density at resonant frequency has increased from 1.4 to 1.8.

In Fig. 12, resonant frequency is also lowered by increasing the load at a spring constant of 26.27. The difference of resonant frequency between those three lines is similar to the result of spring constant 10.51. However, the power densities between green and red line are almost the same. The difference between blue and green line is around 0.2.

In Fig. 13, resonant frequency is also lowered by the increasing load at a spring constant of 208.40. Again, the difference of resonant frequency between those three lines is still similar to the result of spring constant 10.51, and the difference between blue and green line is still smaller than the difference between green and red line. The power densities in blue and green line are very close at this time, and the difference is around 0.03. The power density difference between green and red line is about 0.25.
Figure 11: Test results of spring constant 10.51 N/m.

Figure 12: Test results of spring constant 26.27 N/m.
5.2. Effect of Spring on the Operation Frequency of the Energy Harvester

In the following graphs-Figs. 13, 14 and 15, each graph shows the effect of different spring constant in each of the mass type.

In Fig. 14, from the line of spring constant 10.51 to the spring constant 26.27, the resonant frequency is increasing, but the power density is decreased. However, the line of the spring constant 208.40 shows an opposite result. The resonant frequency decreased and the power density increased.

In Fig. 15, similar to Fig. 14 the resonant frequency of the line of the spring constant 26.27 is higher than the line of the spring constant 10.51, but the power density is much lower. In addition, the line of the spring constant 208.40 has a decreased resonant frequency and an increased power density.

In Fig. 16, the resonant frequency of the line of the spring constant 26.27 is higher than the line of the spring constant 10.51, but the power density is lower. The resonant frequency of the
line of the spring constant 208.40 is smaller than the line of the spring constant 26.27. However, the power density between spring constant 208.40 and 10.51 is only a little higher.

Figure 14: Test results of mass type 1.

Figure 15: Test results of mass type 2.
Figure 16: Test results of mass type 3.

5.3. Effect of Impedance on the Operation Frequency of the Energy Harvester

In Fig. 17, when spring constant = 10.51, and loading for beam 1=2.137 g and beam 2= 2.342 g, the experiment has been done under two different impendence connected. As the figure shown, comparing the results between 5 kohm and the 10Mohm, the resonant frequency in the 10 Mohm is a little higher than the result of 5 kohm, around 1 Hz. The power density in the 10 Mohm is also higher than the 5 kohm, and is about 0.2  higher.

Fig. 18 shows the experiment results under 5 kohm and 10 Mohm impendence when spring constant = 26.27, and loading for beam 1 = 2.137 g and beam 2 = 2.342 g. The resonant frequency in the 10 Mohm is a little higher than the result of 5 kohm, around 1 Hz. The power density in the 10 Mohm is much higher than the 5 kohm, about 0.5  higher.
Figure 17: The influence of loaded impedance on the resonant frequency (beam (1) = 2.137 g, beam (2) = 2.342 g, spring rate = 10.51 N/m).

Figure 18: The influence of loaded impedance on the resonant frequency (beam (1) = 2.137 g, beam (2) = 2.342 g, spring rate = 26.27 N/m).
CHAPTER 6
CONCLUSION AND FUTURE RESEARCH

In this thesis, a basic prototype of a frequency-adjustable wide band energy harvester system have been built. From the experimental observation, the following conclusions are drew

- The resonant frequency can be adjusted to the lower frequency and the power output can be increased by adjusting the added masses.

- The original resonant frequency of only one single piezoelectric beam is 60 Hz. The structure of two piezoelectric beam connecting with a spring reduced the resonant frequency. However, the experiment didn’t show how the different spring constant affect the resonant frequency.

- The impedance affects the power density greatly; the higher impedance, the higher power density. In addition, the higher impedance increases the resonant frequency by a small amount.

According to the discussion of the theoretical background and the experiment result, both of them suggest that adjusting the loaded mass actively may be a promising method to tuning the resonant frequency of the energy harvester to match the source frequency for the maximum power output. With these results and a future research on the effects of the spring constant, a database of the factors, which affect the resonant frequency and the power output of the energy harvester system, can be established. Future researchers or companies may be able to conveniently apply the frequency-adjustable energy harvester system into more fields. Furthermore, in this research, the adjusting is made manually. Thus, making the frequency self-adjustable is our future research efforts.
REFERENCES


