An Experimental Model Piezoelectric Cantilever Beam for Energy Harvesting

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Abstract

Research of energy harvesting is increasing rapidly over last decade. In this study has effort in laboratory scale of energy harvesting with a piezoelectric cantilever beam. The harvester is placed in the middle of the cantilever beam to simulate. This paper is intended to investigate piezoelectric energy harvesting from vibration induced by vertical loads. The design of Cantilever beam configuration piezoelectric is analyzed by finite element method (FEM) to get the first mode of the system. The prediction result by finite element software for the first mode is 91,24 Hz. The effect of displacement, velocity, acceleration with Piezoelectric moving load function on the produced power also investigated in this paper. The experimental result shows the studied mode shape variable can be effected on the energy harvesting result. Lastly, the research results prove that the theory of vibration is the highest voltage is located in the natural frequency of the system.

Keywords: Piezoelectric, cantilever, beam, mode-shape, vibration, voltage.

1. Introduction

The utilization of structure vibration is used for capturing energy from vibration environment is a solution to increase the energy source in the rural area. Among different approach to collect vibration component moving to power energy such as vibration from rotary equipment [1][2], railroad application [3] and structural health monitoring [4]. The most popular research about vibration energy harvesting is piezoelectric with environments component.

Piezoelectric research is mostly done to increase the power output of a particular vibration source. Improper piezo design will cause low the efficiency of the energy harvested [5]. Theoretically, in mechanical vibrations, a system that resonates at a frequency that coincides with the natural frequency of the system will produce maximum electrical power. One thing that needs to be proved in this paper is the opinion from Liu that results in a solution that the output power will drop when the excitation frequency shifts away from the natural frequency of the mechanical system[6]. Many studies use adaptive adjustments to conform to the natural frequency of the piezo system, as did by Clark using the shunt method to adjust the resonator frequency of the piezo system [7]. The study also studied in this paper is the evaluation of structural responses, in this case, is the material and geometry functions of the cantilever beam to external excitation functions, some studies also do the same regarding checking the diversity of materials and geometry associated with the excitation function with statistical approach[8][9].

Typically modeling in piezoelectric for energy harvesting used the simplification of single degree of freedom (SDOF)[10]. SDOF modeling done in this paper using Finite Element Method (FEM) approach. Initial modeling will illustrate the characteristics of the cantilever beam used, such as the vibration mode occurring in some natural frequencies of the cantilever beam system. In this study present distributed parameter solution from cantilever beam with a connection to piezoelectric. The steady state voltage response is measured in such a way that measurements of the vibration mode predicted by the finite element method (FEM) using ANSYS software. Validation through experiment aims to know the role of vibration mode at the natural frequency of the system against the amount of voltage generated.

2. Governing Equation and Theory

There are basically has two types of piezoelectric materials: piezoceramics such as Lead Zirconate Titanate (PZT) and piezopolymers such as Polyvinylidene Fluoride (PVDF)[11]. The workings of the piezoelectric depend on how the material undergoes a bending process. The mechanical and electrical functions of piezo electric can be described in the following equation:

$$S = S^E \cdot T + d^t \cdot E \tag{1}$$

$$D = d \cdot T + \varepsilon^T \cdot E \tag{2}$$

The most useful mode of vibration in piezoelectric is mode one because this mode occurs in the first natural frequency of beam cantilever system. A cantilever beam subjected to free vibration, and the system is considered as a continuous system in which the beam mass is considered as distributed along with the stiffness of the shaft, the equation of motion can be written as:

$$\frac{d^2}{dx^2}\left\{EI(x)\frac{d^2Y(x)}{dx^2}\right\} = \omega^2 m(x)Y(x) \tag{3}$$

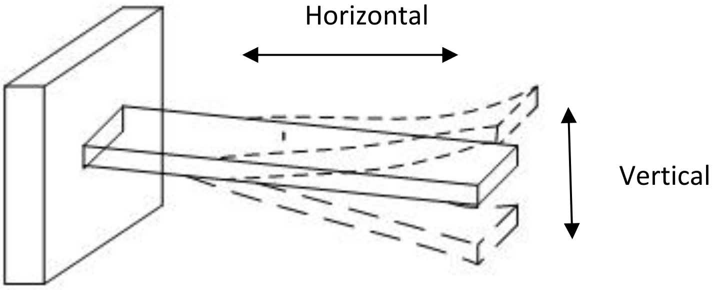


Fig. 1: The beam free vibration

Based on fig.1 boundary conditions for a cantilever beam

$$at\ x = 0, Y(x) = 0, \frac{dY(x)}{dx} = 0 \tag{4}$$

$$at\ x = l, \frac{d^2Y(x)}{dx^2} = 0, \frac{d^3Y(x)}{dx^3} = 0 \tag{5}$$

for beam cantilever under free vibration get :

$$\frac{d^4Y(x)}{dx^4} - \beta^4 Y(x) = 0 \tag{6}$$

with ,

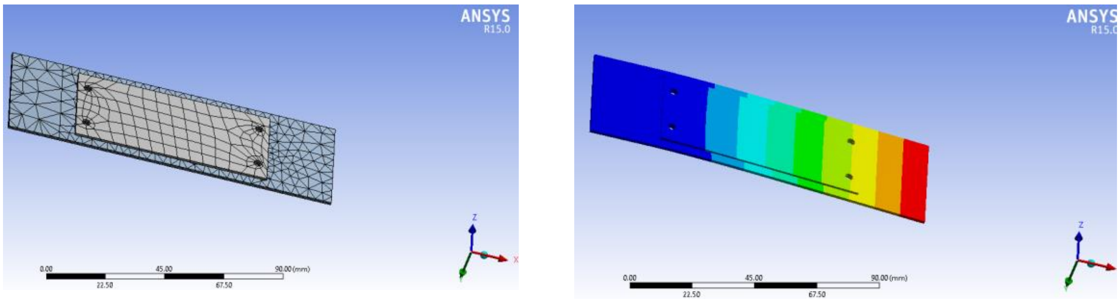
$$\beta^4 = \frac{\omega^2 m}{EI} \tag{7}$$

The mode shape for a continuous cantilever beam can be written as [11]:

$$f_n = \frac{{V_n}^2}{2\pi}\sqrt{\frac{EI}{12AL^4}} \tag{8}$$

3. Cantilever Beam FEM Result

Modeling a cantilever beam using three-dimensional model. Piezoelectric is placed in the middle of the cantilever beam as shown in Figure 2. As shown in Figure 2, the meshing and modal analysis model are simulated using ANSYS software with FEM approach. With Modal analysis simulation it is known that the first mode in the cantilever beam system is 91 Hz with a single moving vertical direction. The design of the Mode shape for cantilever beam is shown below:



(a) Meshed model (b) Frist mode at 91 Hz

Fig. 2: The Cantilever beam FEM simulation

The experiment was carried out using mini shaker as a tool to excite cantilever beam system with a peak to peak force produced by a mini shaker is 20 N, so that graph of response function to amplitude displacement, velocity, and acceleration, according to figures 3, 4 and 5, respectively.

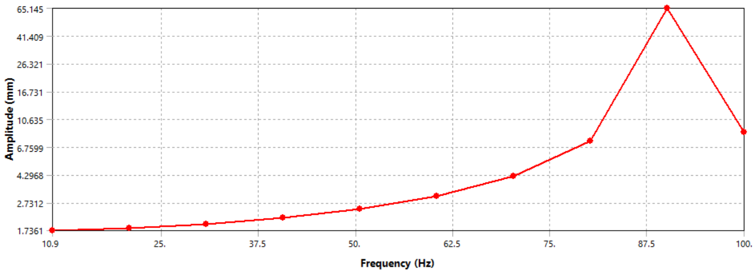


Fig. 3: Function response to amplitude displacement

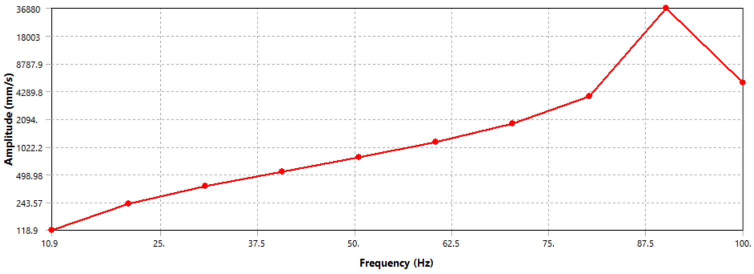


Fig. 4: Function response to amplitude velocity

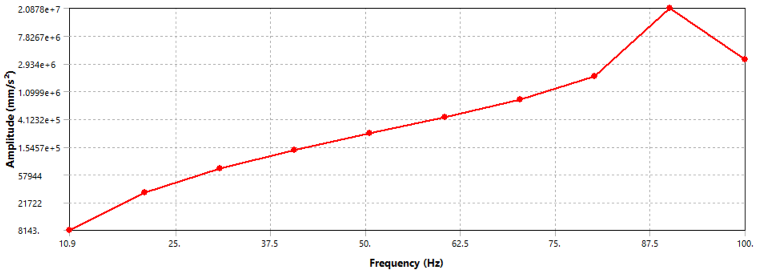


Fig. 5: Function response to amplitude acceleration

4. Experimental result and discussion

3.1. Experimental setup

Cantilever beam energy harvester is connected to a fixed support. The piezoelectric coupled with cantilever beam attached used the bolt in a location in the middle of the beam. In figure 6 and 7 are shown the side view of experimental setup and the scheme of experimental setup.

Fig. 6: the side view of experimental setup

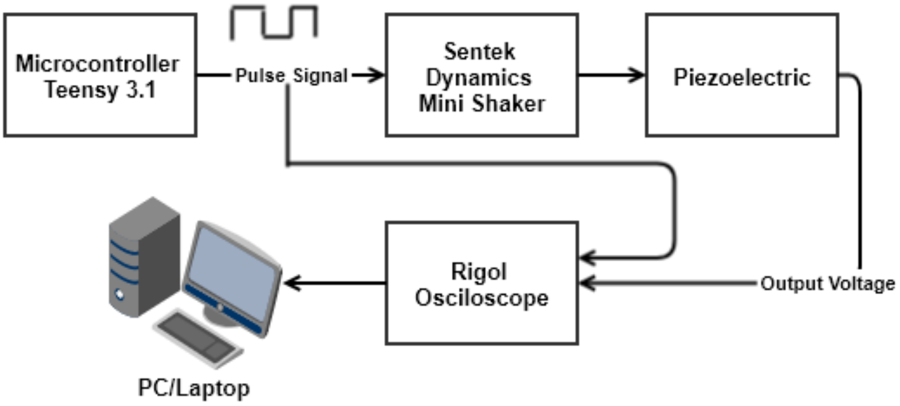
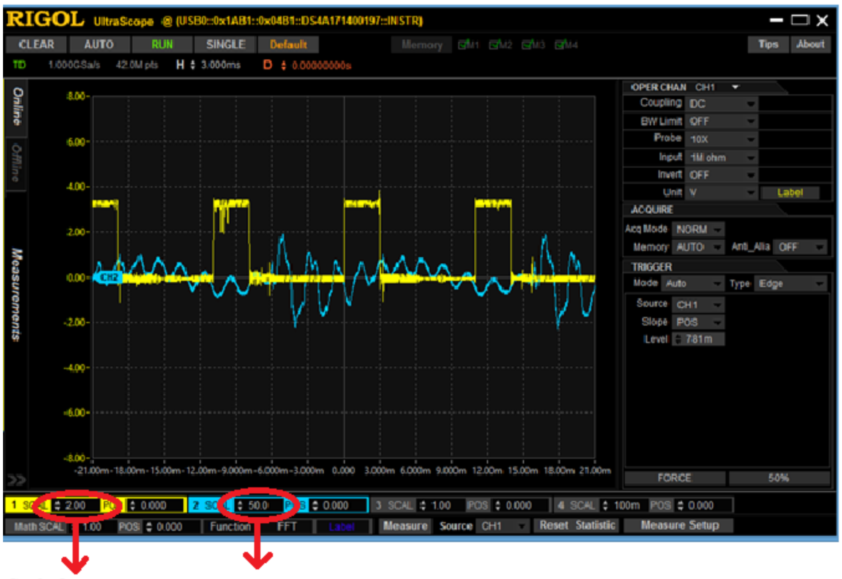


Fig. 7: Experimental setup for piezoelectric data acquisition

In this research, the experimental setup shown in Figure 7. Teensy 3.1 Microcontroller is used to generate pulses (square wave signal as an input signal) in Frequency of 30 Hz , and 91.24 Hz. These pulses will trigger the mini shaker to generate the vibration, the frequency of vibration depends on the frequency of the pulse. The vibration from the mini shaker is coupled to the piezoelectric, so the piezoelectric will produce the electrical energy (output signal in voltage). Input signal from Teensy 3.1 and output signal from piezoelectric are measured using oscilloscope, and then the data from oscilloscope are recorded to the PC/laptop.

3.2. Result and discussion

In the test used 2 different case study there are 30 Hz and 91 Hz. Fig 8 Shown the result of output voltage characteristic from piezoelectric with the 91.24 Hz input pulse vibration. According to the result, the characteristic of output voltage has identical cycle in every two cycle of input pulse (two periode of input pulse). The highest postive voltage is 45.3 V and the highest negative voltage is -53.1 V. The detail of one cycle of piezoelectric output voltage is shown in Fig 9



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CLEAR AUTO RUN SINGLE Default

1.000GSa/s 42.0M pts H 3.000ms D 0.000000000s

OPER CHAN CH1
Coupling DC
BW Limit OFF
Probe 10X
Input 1M ohm
Invert OFF
Unit V

ACQUIRE
Acq Mode NORM
Memory AUTO
Anti_Alia OFF

TRIGGER
Mode Auto
Type Edge
Source CH1
Slope POS
Level 781m

1 SCAL 2.00 POS 0.000
2 SCAL 50.0 POS 0.000
3 SCAL 1.00 POS 0.000
4 SCAL 100m POS 0.000
Math SCAL 1.00 POS 0.000
Source CH1

Scale 2 represent
2 V per Division

Scale 50 represent
50 V per Division

Fig 8. Data Capturing from Oscilloscope with The Input Pulse 91.24 Hz

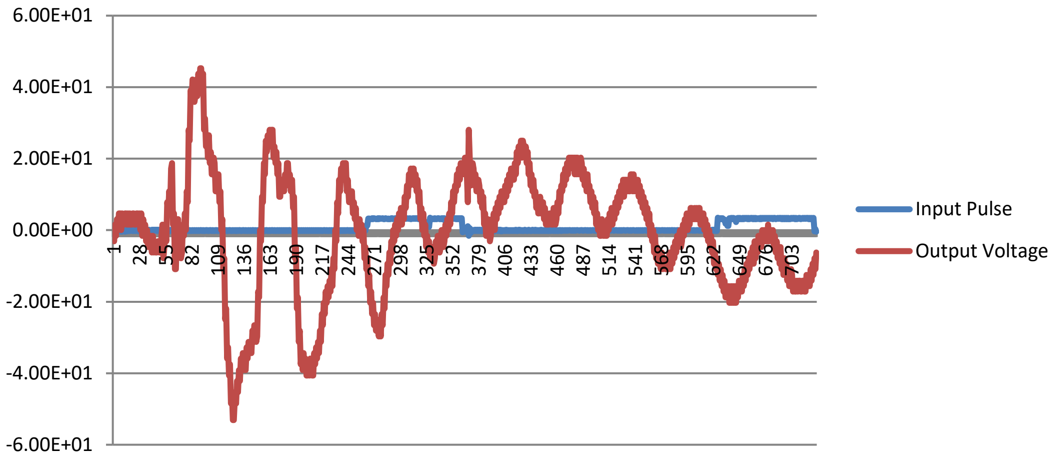


Fig 9. One Cycle of Piezoelectric Output Voltage at 91.24 Hz Vibration

Because of the output voltage has a negative value, we have to create the filter if we want to use the piezoelectric as a source of electrical energy. The simple way to filter the output by using bridge rectifier. After using the bridge rectifier as a filter, the output voltage that has a negative value will be converted to become a positive value, then the output voltage will looks like in the Fig 10. With this filter the highest positive voltage is 53.1V and the average voltage is 12.493 V.

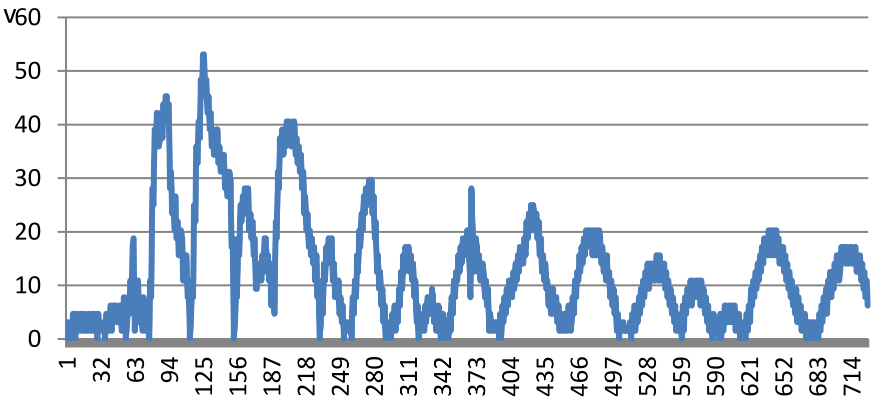
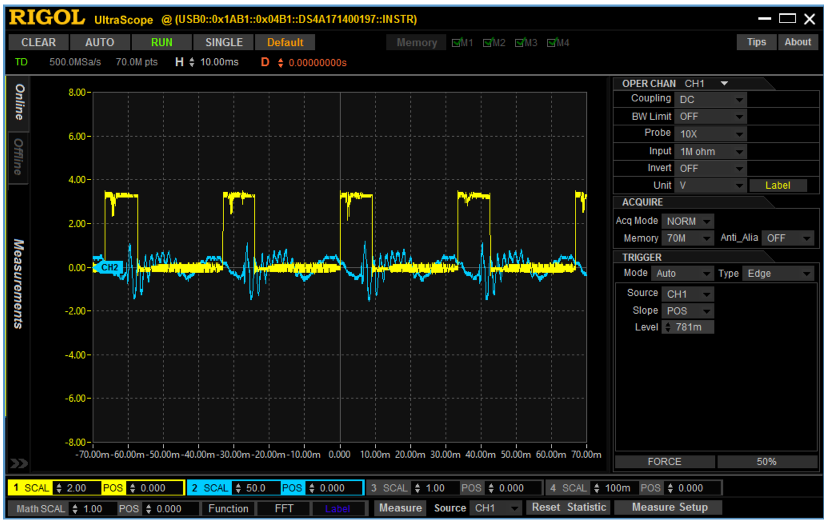


Fig 10. Output Voltage from Piezoelectric at 91.24 Hz Vibration with Bridge Rectifier Filter

Fig 11. Shown the result of output voltage characteristic from piezoelectric with the 30 Hz input pulse vibration. From the measurement results, it was found that at 30 Hz vibration obtained the output voltage is smaller than the previous measurements.The detail of one cycle of piezoelectric output voltage at 30 Hz is shown in Fig 12. The highest of positive voltage is 26.6 V and the highest negative voltage is 34,4 V.



TD 500.0MSa/s 70.0M pts H 10.00ms D 0.00000000s

OPER CHAN CH1
Coupling DC
BW Limit OFF
Probe 10X
Input 1M ohm
Invert OFF
Unit V

ACQUIRE
Acq Mode NORM
Memory 70M
Anti_Alia OFF

TRIGGER
Mode Auto
Type Edge
Source CH1
Slope POS
Level 781m

1 SCAL 2.00 POS 0.000
2 SCAL 50.0 POS 0.000
3 SCAL 1.00 POS 0.000
4 SCAL 100m POS 0.000
Math SCAL 1.00 POS 0.000
Source CH1

Fig. 11: Data Capturing from Oscilloscope with The Input Pulse 30 Hz

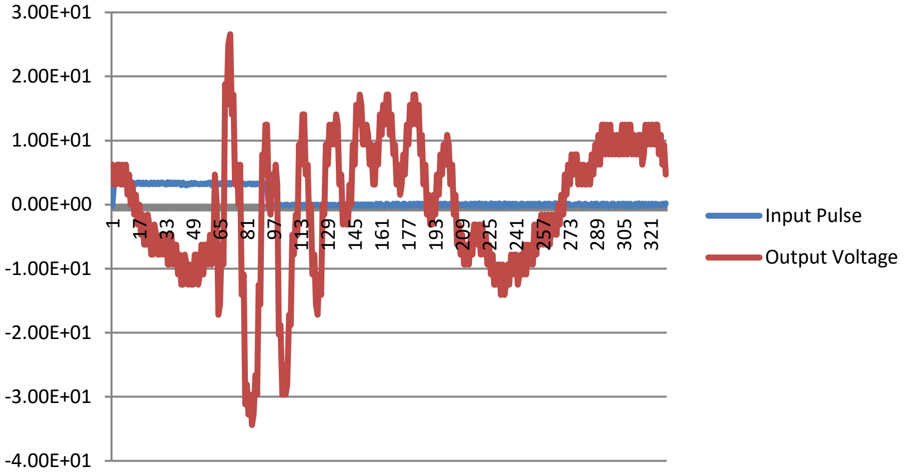


Fig. 12: One Cycle of Piezoelectric Output Voltage at 30 Hz Vibration

Fig 13 Show the result of output voltage with bridge rectifier. At 30 Hz vibratrion, the voltage average of piezoelectric is 8.623 V.

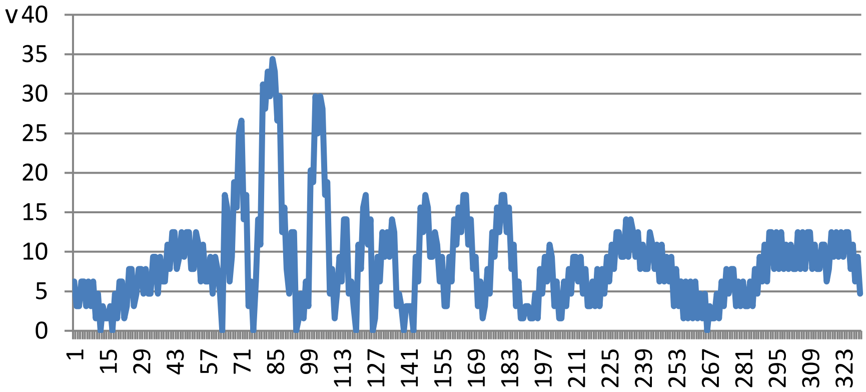


Fig. 13: Output Voltage from Piezoelectric at 30 Hz Vibration with Bridge Rectifier Filter

5. Conclusion

Cantilever beam energy harvester are the most popular devices found in the literature, there are still much more to learn. The research results prove that the theory of vibration is the highest voltage is located in the natural frequency of the system. From this research note that piezoelectric is able to produce the largest output voltage at frequency 91,24 Hz. This is particularly interesting to be studied more deeply especially for research related to the design of appropriate energy storage systems for piezoelectric energy harvesting.

6. Nomenclature

S = Mechanical strain
D = Electrical Displacement
T = Mechanical stress
E = A simply Hooke's law relating strain and stress
S^E= Matrix of elasticity under condition of constant electric field
d and d^t = the matrices for the direct and the reverse piezoelectric effect where the superscript t means the transposed matrix
ε^T = dielectric permittivity under a zero or constant stress
I = The moment inertia of the beam cross section
Y(x) = Displacement in vertical direction (see figure 1)
x = Distance in horizontal measured from fixed end.
ω = Natural frequency
m = mass per unit length
f_n = Natural frequency
A = Area
L = Cantilever beam length
v_n = 1,875 for fundamental mode (first mode).

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