www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

CANTILEVER BEAM BASED PIEZOELECTRIC ENERGY HARVESTER

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Submitted: Oct. 15, 2015 Accepted: Nov. 10, 2015 Published: Dec. 1, 2015

Abstract- With the application of wireless sensor networks become widespread, supply energy for these wireless sensors proves to be a significant issue. Moreover, for the ambient vibration lies everywhere, the vibration can supply energy for the wireless sensor via energy harvester. The piezoelectric energy harvester becomes the research focus for the simple structure and higher energy conversion efficiency. Due to the transcendental equation in distributed parameter model, the numerical method is become powerful complement for theoretical and experimental method. This paper uses ANSYS to analyze the single piezoelectric cantilever in static analysis, model analysis, harmonic response analysis and mechanical-electrical coupling analysis. It analyzes the natural frequency and voltage effect from four aspects which are length to thickness ratio, length to width ratio, the substrate thickness to piezoelectric thickness ratio and seismic mass. Test and measurement for piezoelectric energy harvester is conduct on the testing platform. Macro cantilever beam piezoelectric energy harvester are tested and measured.

Index terms*:* piezoelectric；energy harvester；mechanical-electrical coupling.

I. INTRODUCTION

With the development of wireless sensor networks (WSN), Embedded Systems, Radio Frequency Identification(RFID) and all kinds of implantable MEMS sensor electronic products are becoming miniature, integrated, low power consumption and low cost[1~3]. Power supply for WSN has become the most prominent issues[4]. These devices are dormant in most working period and belong to intermittent work pattern[5].In addition, as using MEMS technology, power of the sensors is very low even in working state. According to Moore's Law, the development of microelectronics technology has made the controllers' and sensors' power consumption decreased to tens to hundreds of microwatts[6].And It is still decreasing, the power of transmitter and receiver of common WSN can decrease to a few milliwatts to tens of microwatts[7].

Moreover, as for the limitation by the application of WSN, power transmission or battery replacement is becoming a impossible task. In addition, for some implanted environment such as cardiac pacemakers, radioactive conditions or weapons systems, size, cost and working conditions of energy supply has more higher requirements. Researchers have been trying to find and develop new energy resource to replace traditional energy sources. Traditional power supply apparently cannot satisfies the special requirements of emerging technologies. A new power supply must be found to overcome so much shortcomings of the conventional battery and wired power when confront with a variety of miniature wireless sensors and embedded devices.

II. RELATED WORKS

Hausler[8] simulated the PVDF piezoelectric plate into the dog's chest and harvest energy from the dog's breathing movement. Shad Roundy[9] used piezoelectric energy harvester from microwave ovens. Shad Roundy added seismic mass on the end of the cantilever beam and lowed the natural frequency and increased the amplitude and power. Rajendra[10] fabricated MEMS piezoelectric energy harvester and powered a WSN sensor. Yasser Ammar[11] used cantilever beam harvester and asynchronous DC-DC transfer circuit to harvest energy and deposited in the battery. Zhonglin Wang[12] used ZnO nano-wires to harvest energy that proved to be more efficient and can power micro drop-in medical devices. Dongna Shen[13] fabricated MEMS piezoelectric cantilever beam energy harvester which has seismic mass on the end and very low frequency and higher efficiency to harvest energy. R. Elfrink[14] studied chip-level vacuum package micro energy harvester which increased the output power exceed 100 times. Alex Mathers[15] designed and fabricated a cantilever beam harvester made of PDMS and PMN-PT. Li Wei[16] designed vibration-based miniature generator and investigates miniature electric generators that are constructed with piezoelectric benders. Arman Hajati[17] fabricated a nonlinear ultra-wideband MEMS which used Duffing resonance.

III. FINITE ELEMENT METHOD

In the field of science and technology, although many mechanical and physical problems can write constitutive equations and corresponding boundary conditions. But analytical methods can solve only a small number of relatively simple problem. For most problems, the solutions of nonlinear equations or complex shape, the analytical solution cannot be obtained. Typically numerical solution is used to solve these problem. It said that with theoretical and experimental methods which called three elementary research tools. For micro cantilever beam energy harvester, finite element method can greatly improve the accuracy and efficiency of micro energy harvester design. In recent years, commercial finite element software as ANSYS, ABAQUS, etc. provide piezoelectric coupling unit gives consistent results to theoretical analysis.

a. Modeling of single cantilever beam energy harvester

Micro piezoelectric energy harvester can generate energy according to requirements of environmental vibration. It is required that the working frequency of micro piezoelectric energy harvester and environmental vibration are matched. And the harvester must be sensitive to the vibration and simple structure to fabricate.

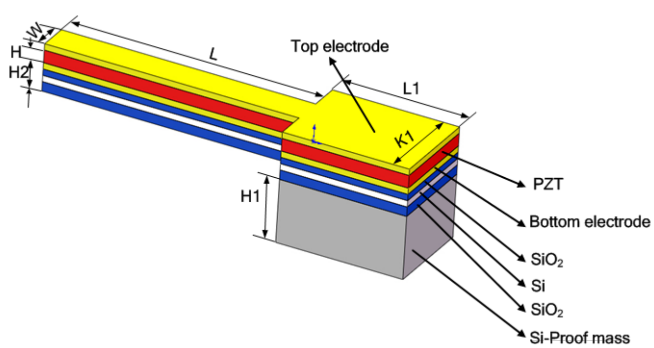


Figure 1 diagram of cantilever structure

Three structure of piezoelectric cantilever beam are heterogeneous double layer, double layer, sandwich structure. Considering the requirements of MEMS manufacture processing, the structure of the piezoelectric cantilever is shown as Figure 1. The upper and lower electrode layer can collect the charge that generate by the piezoelectric layer. The insulation layer prevent charge lost which constituted by the elastic layer. The seismic mass can decrease the natural frequency of cantilever and make it close to the natural frequency of environmental vibration. On the other hand, the seismic mass can increase the inertia force and deformation which increases the input mechanical energy and the output power will increase correspondingly.

b. Simplify structure and size

In solid modeling, appropriate approximation and simplification are applied, the corresponding mathematical model can be established. Two principles of approximation and simplification shown as below. 1) Accurate solution of the characteristics of piezoelectric energy harvester can be obtained by software simulations. 2)Meet the requirements before the software process and ensure the final accuracy. Under the premise of improving the computing speed and ensuring the accuracy, the mathematical model can omitted insignificant minutiae, such as the thickness of the electrode and the insulating layer is much smaller than the thickness of the other layers in the analysis and simulation. The effect of insignificant on the whole can be ignored while in the calculation and simulation. The size of the energy harvester are shown as Table 1.

Table 1 initial size of cantilever (unit：μm)

description	parameter	value
Cantilever length	L	2000
Cantilever width	W	100
Thickness of PZT	H	2
Height of elastic layer	H2	10
Length of mass	L1	600
Width of mass	W1	200
Height of mass	H1	200

c. Material and element

According to the previous design and analysis, micro piezoelectric cantilever energy harvester is consisted of a piezoelectric layer and an elastic layer that composed of two materials. Piezoelectric material is PZT-5H and elastic layer and the seismic mass is made of silicon as far as the process of MEMS is concerned. Element solid226 is used to mesh PZT, element solid95 is used for mesh silicon cantilever and the mass due to the corresponding coupling piezoelectric material solid226.

IV. STATIC ANALYSIS

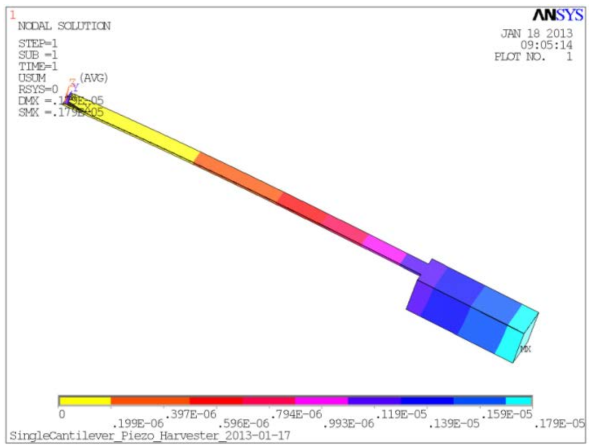
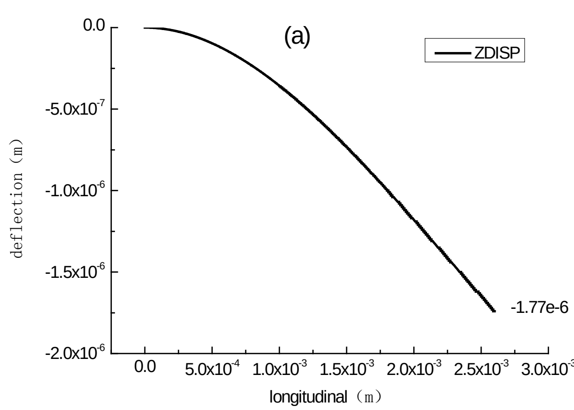


Figure 2 deformation under the effect of gravity

In the manufacture process of MEMS, due to the large length of the cantilever and seismic mass on the end of the beam, so the cantilever would be deflect. It is necessary to verify the stress, strain and deflection. The deformation of the cantilever is shown in Figure 2.The deflection is about 1.8μm in the condition as shown before.



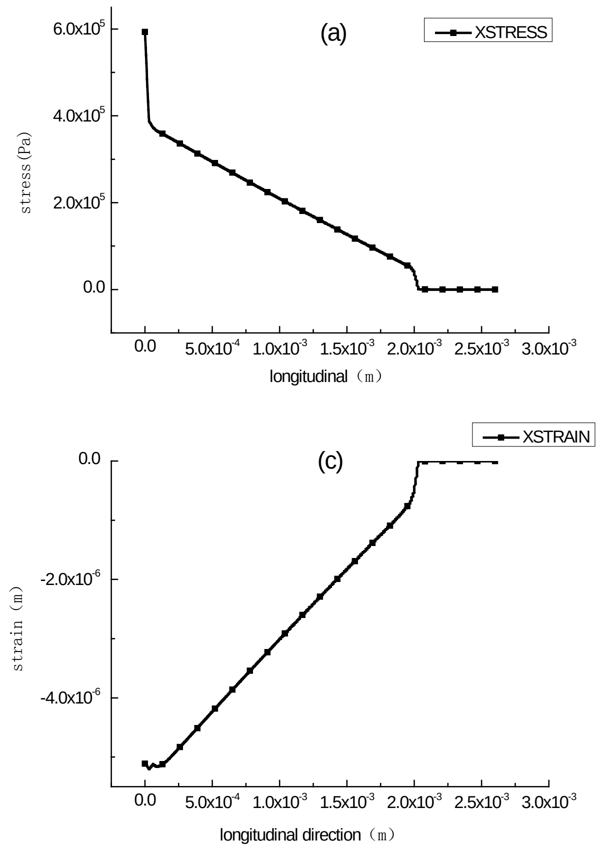


Figure 3 beam deflection and the stress and strain X direction

By finite element analysis, the maximum deflections 1.8μm which lactate at the end of the cantilever and under the effect of gravity. The stress and strain of the surface layer center of the beam is shown in Figure 3(b) and Figure 3(c) respectively. It can be seen that the maximum stress and strain of the beam is located at the roots of the beam. On the other hand, stress and strain is very small on the surface of the mass. The stress and strain drop too drastically at the edge of the seismic mass. It is concluded that PZT material can be overlaid only on the beam while in MEMS processing. The strain is extremely small on the end of the mass, it does not produce the piezoelectric effect.

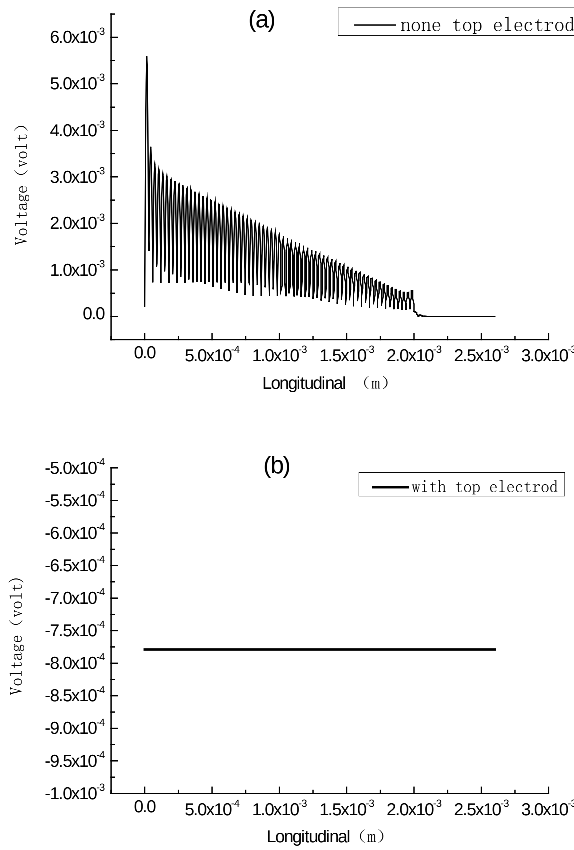


Figure 4 Voltage generate by the harvester under gravity

The voltage distribution of the surface layer center of the beam is shown if Figure 4. If there is no electrode on the PZT layer, the distribution is shown in Figure 4 (a).However, every harvester has electrodes to transmit power which is shown in Figure 4 (b). It can be seen that more close to the root of the cantilever the bending moment if bigger and voltage generate higher, and vice versa. Using electrode to cover the surface, charge collection of the harvester will be more efficient, and the magnitude of voltage will drop.

V. MODAL ANALYSIS

In order to achieve the cantilever resonance, the natural frequency of cantilever must close to the environment vibration frequency. Modal analysis of the cantilever can get the vibration characteristics that including the natural frequencies and modes of vibration. Therefore, the impact of structural size and seismic mass at the end of the cantilever is of great value and easily to get by the simulation. The analysis is done according to the data and the result is shown as Table 2.The modes of first three is shown if Figure 5.

Table 2 The first five natural frequencies

orders	1	2	3	4	5
frequency(Hz)	408	3278	5856	9603	20570

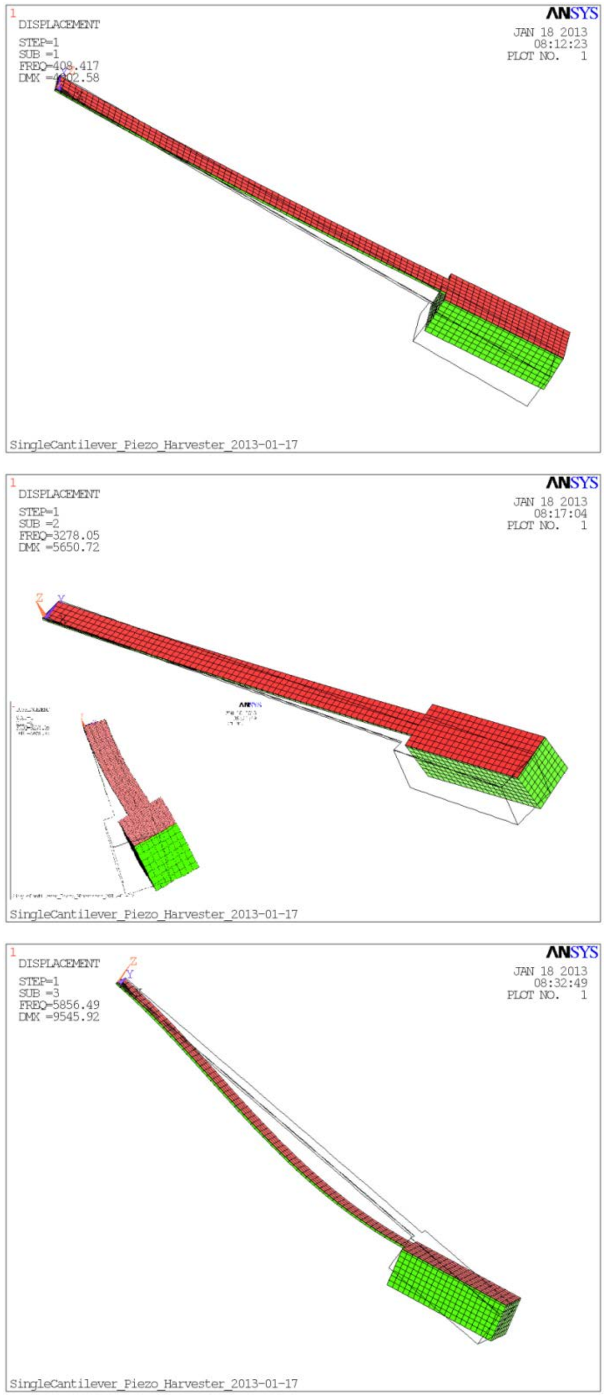
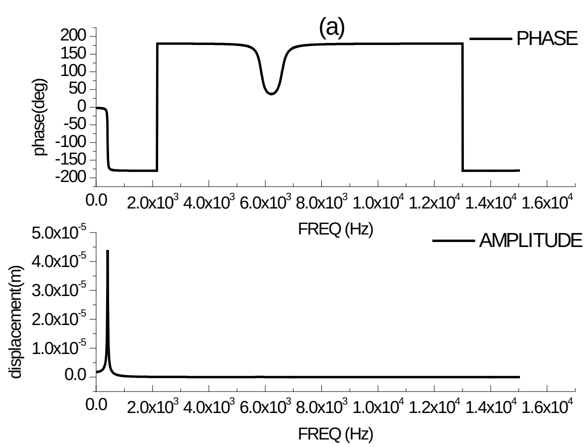


Figure 5 The first three modes

The first picture of Figure 5 shows the first mode of the cantilever. It can be shown that the vibration is a vertical vibration and the PZT will work under 31 mode that power generation is great. The second picture of Figure 5 shows the second mode of the cantilever and the vibration is a torsion vibration and the natural frequency is higher. The third picture of Figure 5 shows the third mode of the cantilever and the vibration is also a vertical vibration but the natural frequency is ten times higher the first mode. So this mode harvest very small power. Generally, the first mode of vibration is considered will make computation more accurately.

VI.HARMONIC RESPONSE ANALYSIS

Excitation that the actual energy harvester received is not purely sinusoidal signal. In theoretical research， numerical research, even experimental research, sinusoidal excitation is used energy harvester by many scholars. This method uses a sinusoidal acceleration applying on the fixed end of the harvester and then study the response signal. Harmonic analysis applies sinusoidal load that the amplitude and frequency is know on the structure. The harmonic displacement of every freedom can be get. Harmonic analysis of energy harvester is a dynamic response when the cantilever is suffered a concentrated time-varying frequency harmonic load. And the output voltage and harmonic frequency will be got through the electro-mechanical coupling module. Given the acceleration is 1g, damping 0.02, harmonic analysis interval is 0 ~ 15000Hz. The result is shown in Figure 6.



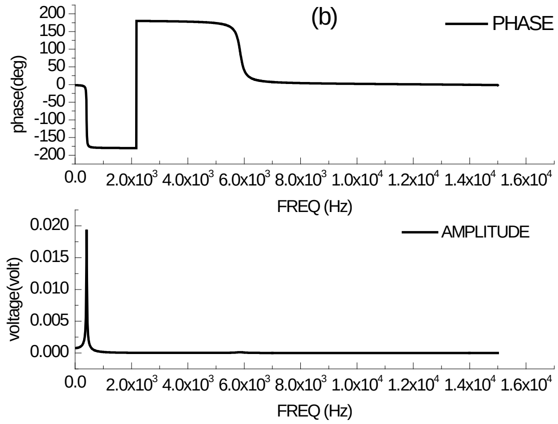


Figure 6 The displacement and voltage of the harvester in harmonic analysis

The maximum displacement is 44.05μm and the maximum voltage that output from the upper electronic plate is 0.019V,which are both shown in Figure 6.Meanwhile, in the first order, second order and third-order natural frequency, amplitude and phase of the voltage have significant deflection. Although in higher-order frequency the harvester will resonating, the vibration amplitude of vibration is very small and so do the voltage. It can be also concluded that the structural's first order natural frequency of the micro cantilever energy harvester must match the excitation frequency of the environment. Energy output will achieve the maximum at that time.

Ⅶ.ELECTROMECHANICAL COUPLING ANALYSIS

Energy harvesting system could not only consider the piezoelectric material and elastic, the external circuit devices should be taken into account. ANSYS has powerful multi-field coupling analysis function. The force field and circuit coupling of energy harvester can be achieved by careful modeling. The coupling molding is shown in Figure 7.

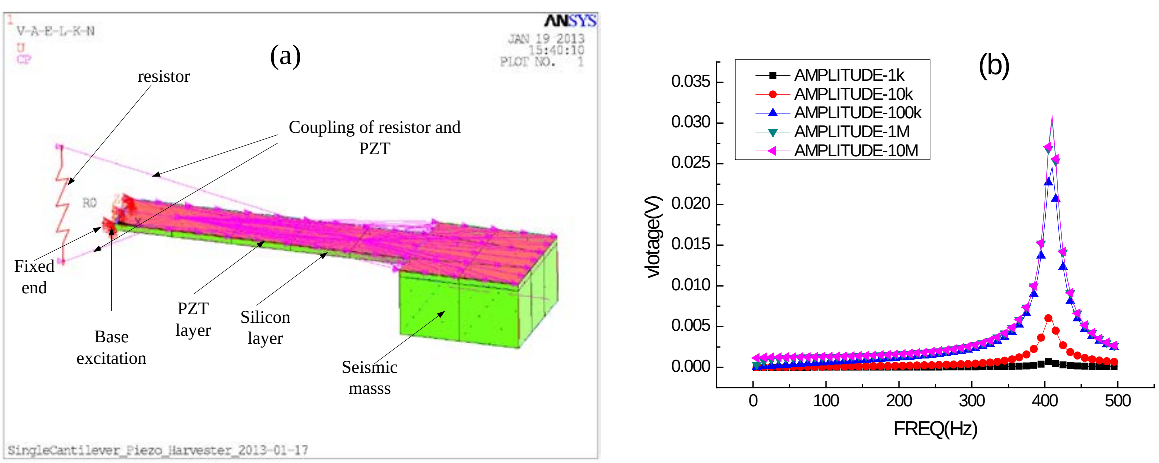
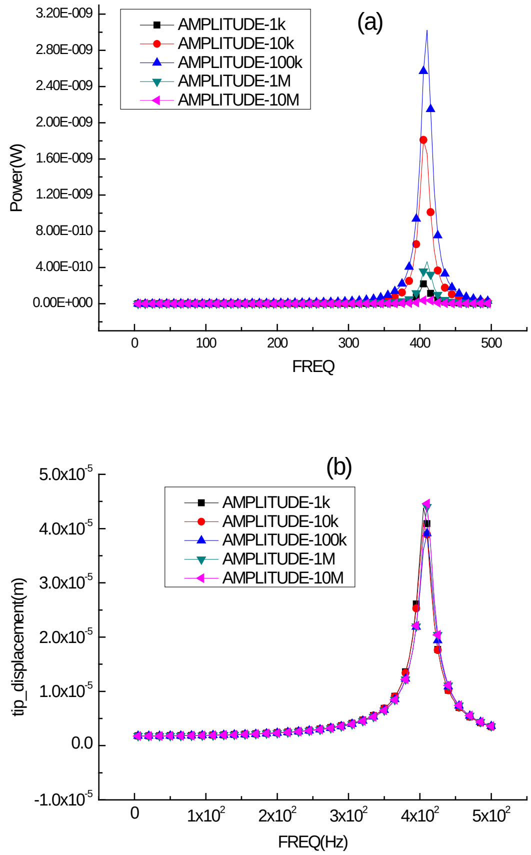


Figure 7 The coupling molding and the voltage of out circuit when connect different resistor

The voltage of out circuit shows in Figure 7(b) when the resistor is 1KΩ，10KΩ，100KΩ，1MΩ,10MΩ respectively. It can be concluded that the voltage of out circuit of a harvester will be maximum when the harvester resonating in 0~500Hz frequency range. The voltage across the resistor will increase with the increase of the resistance value. But it has few increase when the resistance value increase form 1MΩ to10MΩ as shown in Figure7 (b).The power of harvester is a certain value under certain vibration. If the resistance value of external circuit is exceed the inner circuit resistance，the voltage of external will not continue increase.



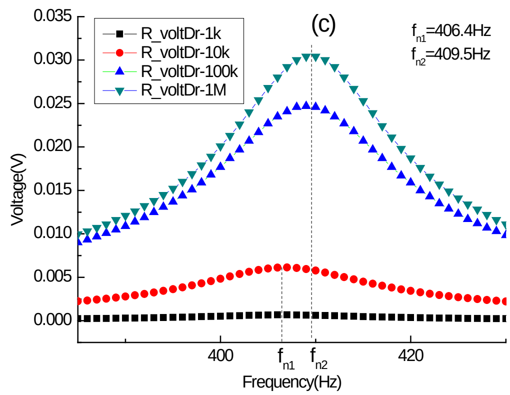


Figure 8 The effect of resistor to power, displacement and resonating frequency

It can be seen from Figure 8(a),the power of external circuit will be maximum only when the harvester begin to resonate. The maximum power of harvester is close to the resistance value. It can be seen from Figure 8(b),the resistance value has little effect to the maximum displacement of the harvester. It can be seen from Figure 8(c),the resistance value has a little effect to the first order natural frequency of the harvester. The frequency will increase a little with the increase of resistance value and it will not increase after the valve exceed certain value. The frequency is 406.4Hz when the resistance is 1KΩ and 10KΩ.Wheras, it will be 409.5Hz when the resistance is 1MΩ.

Ⅷ.EFFECT OF THE STRUCTURAL DIMENSIONS

Due to the capability of the harvester is close to the structure, the easiest and most effective method to adjust the resonating frequency is to adjust the structure parameter of the cantilever. On the other hand, not only the frequency is to be concerned, but the voltage and power should be taken into account. Four parameters are presented here to study the energy harvester performance, which are length to thickness ratio, length to width ratio, the substrate thickness to piezoelectric thickness ratio and seismic mass.

a. Effect of length to thickness ratio

According to material mechanics, more thickness makes greater flexural rigidity. But more length makes the moment of the root greater and strain will be greater too. Length to thickness ratio can reflect the flexural rigidity to a certain extent. Generally, great length to thickness ratio makes the beam more flexible and easily to bend, and vice versa.

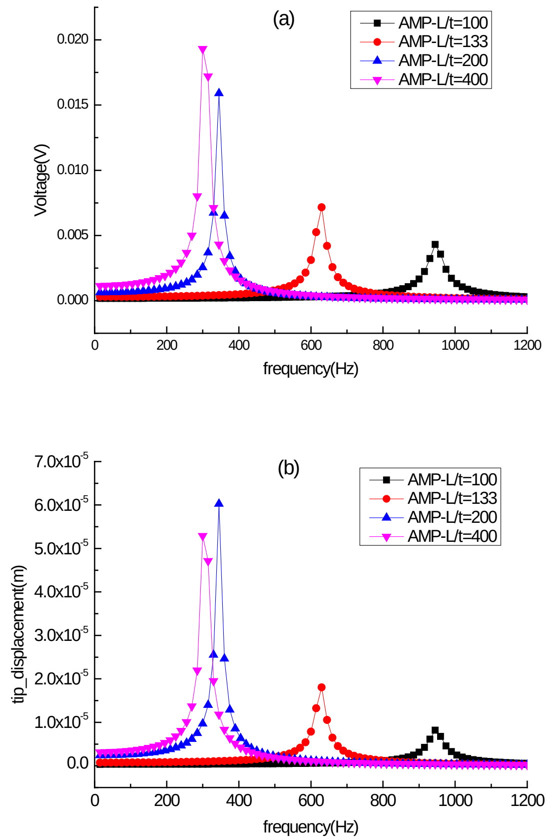
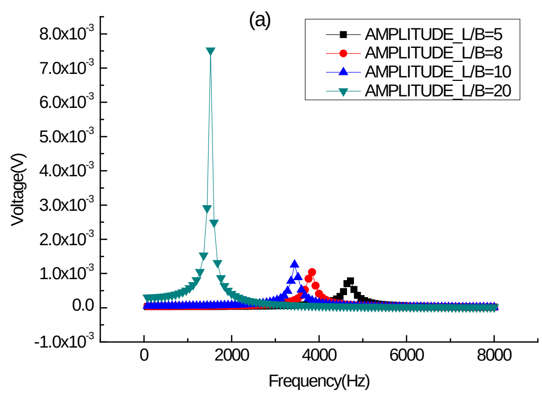


Figure 9 The effect of different length to thickness ratio

It can be seen from Figure 9(a),the first order frequency of the harvester will be decrease with the increase of the length to thickness ratio. But in lower frequency, it is less effective of increase of the length to thickness ratio to decrease the frequency of the harvester. In other words, it is more effective to decrease the frequency of the harvester by increase the length of the cantilever in higher frequency than in lower frequency. On the other hand, the displacement of the harvester will increase with the length to thickness ratio. But if the ratio exceed 200 shown in Figure 9(b),the displacement will decrease.

b. Effect of length to width ratio



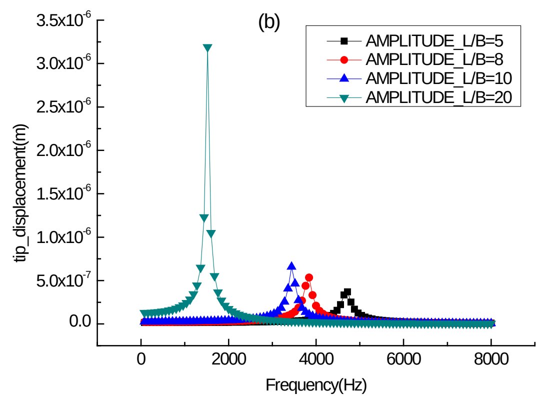


Figure 10 The effect of length to width ratio

Generally, little length to width ratio makes the cantilever more flexible and easy to bend, vice versa. It can been seen from Figure 10,with the increase of the length to width ratio the first order resonating frequency will decrease. The displacement of the harvester will increase and voltage of external circuit will increase too.

c. Effect of substrate thickness to piezoelectric thickness ratio

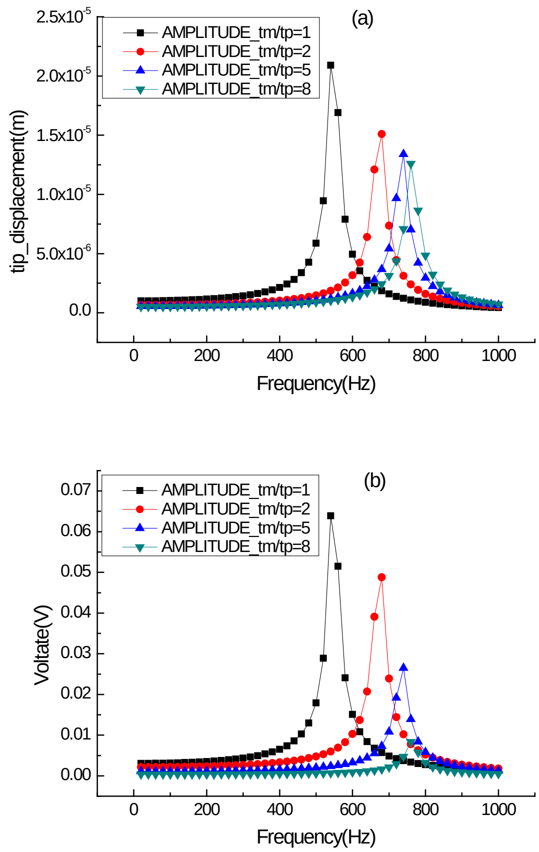


Figure 11 The effect substrate thickness to piezoelectric thickness ratio

It can been seen from Figure 11,with the increase of PZT layer, the voltage of the harvester will increase under the resonant frequency. Because the PZT modulus is smaller than the elastic silicon, increase the thickness of PZT can decrease the resonant frequency of the harvester. On the other hand, more lower resonant frequency makes the top displacement of beam more bigger.

d. Effect of seismic mass

More big seismic mass makes the frequency of the energy harvester more lower. Here the volume of the seismic are represent by their height which are 100， 190， 300 and 500.

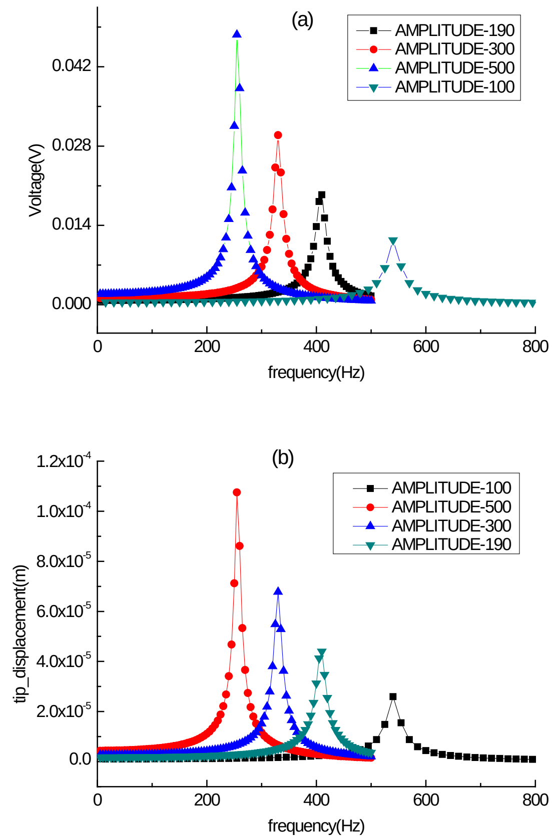


Figure 12 The effect of seismic mass

It can been seen from Figure 12,biger seismic mass makes the frequency lower. At the same time, the maximum displacement and the voltage of external circuit of the energy harvester will increase too.

According to the law that have been found in this paper, a more optimized piezoelectric cantilever can be designed. To decrease the natural frequency to close to the environment vibration and increase the output voltage, the length of the cantilevercan be increased and reduce the width and height, or increase the seismic mass. However, due to the limitation of MEMS process, as well as the stress and fatigue limit of the materials, these factors must be taken into account synthetically.

Ⅷ.MEASUREMENT AND TEST OF PIEZOELECTRIC ENERGY HARVESTER

Macro piezoelectric energy harvester at centimeter scale are measured and tested. The measurement are including such instrument as signal generator, power amplifier, dynamic signal analyzer, multi-meter etc.

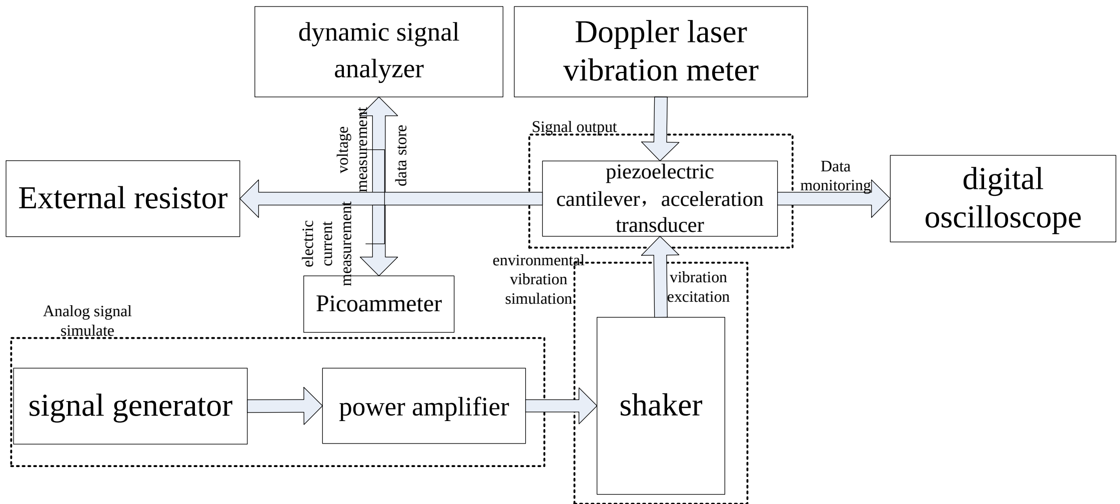


Figure 13 The architecture of the measurement

The schematic of the measurement is shown as Figure 13.Three part are included such as analog signal simulate, environment vibration simulation and signal output.

a. Working principle of test system

The signal generator send the excitation signal to power amplifier, then the amplified signal transmits to the shaker. Sinusoidal signal is the most often used signal. The shaker vibrates vertically depend on the signal. The piezoelectric energy harvester is fixed on the customized fixture which is connected on the shaker rigidly. Voltage is produced from the piezoelectric energy harvester when it is excited by the shaker. If the voltage is input the dynamic signal analyzer or the digital oscilloscope, the voltage is the open circuit voltage. If the harvester is connected with resistors, the resistor can be regard as circuit load. The voltage that measured by the dynamic signal analyzer or the digital oscilloscope are load voltage. Circuit current can be measured by picoammeter. The picture of test system are shown in Figure 14.

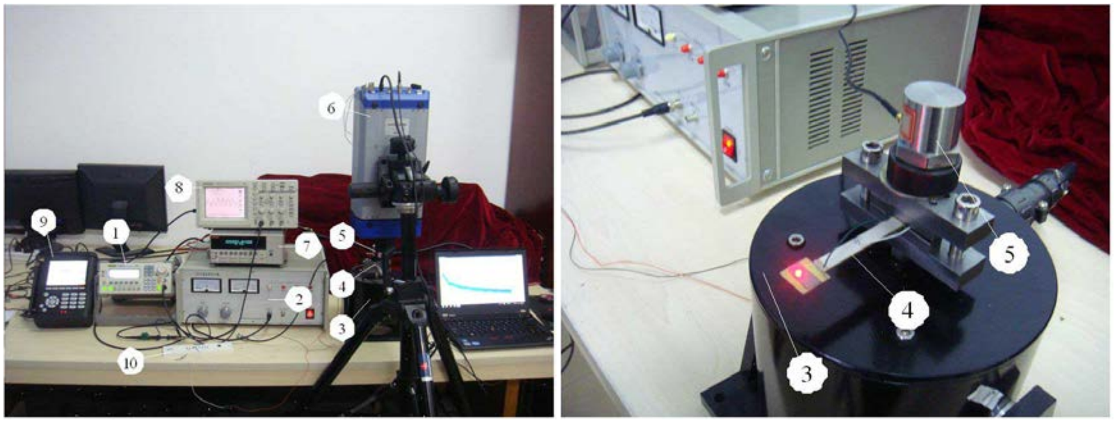


Figure 14 The picture of the measurement

(1.signal generator 2.power amplifier 3.shaker 4.energy harvester 5. acceleration sensor 6.Doppler laser vibration meter 7.picoammeter 8.digital oscilloscope 9. dynamic signal analyzer)

b. Measurement and test of the energy harvester

Piezoelectric energy harvester works under the simulated environments and the waves and voltage can be seen from the oscilloscope. At the same time, dynamic signal analyzer will record the acceleration and the voltage that piezoelectric energy harvester output.

When the working frequency reach the natural frequency, the piezoelectric cantilever beam will resonating and the amplitude of the vibration will be maximum, stress in the PZT layer will be maximum. This could be used to determine the natural frequency and maximum voltage of the device. The frequency of the signal generator can be roughly adjusted at first. You can scan from lower frequency to higher frequency and observe the voltage output on the oscilloscope. When the voltage changes from low to high, then from high to low, the measurement and test scope can be determined. Then finely adjusts the frequency in this scope and record the frequency, voltage and acceleration signal correspondingly. After the data processing, the frequency response curve can be gotten.

c. Output of AC voltage

AC voltage of the energy harvester on oscilloscope and dynamic signal analyzer are shown in Figure 15. CH1 is the acceleration signal and CH2 is the voltage. The result of Doppler laser vibration meter is shown in Figure 16 that the excitation frequency of the harvester is 125Hz.

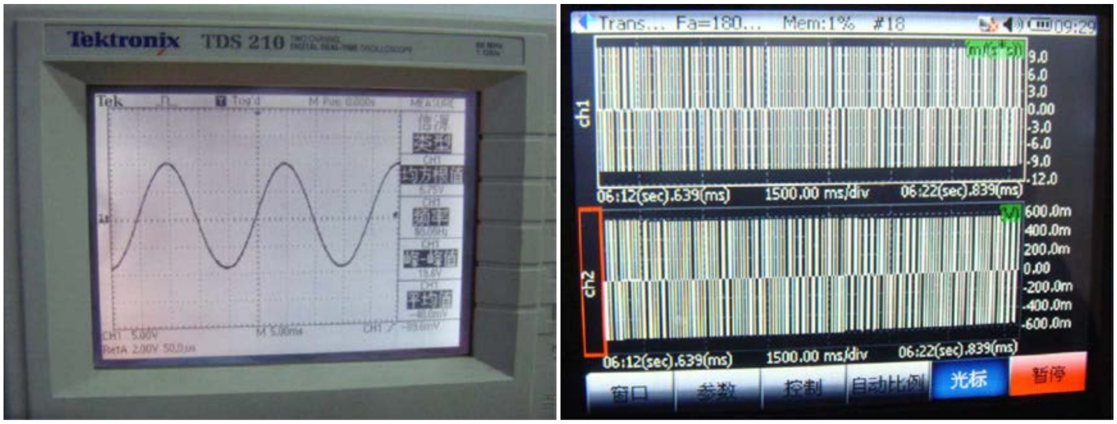


Figure15**AC voltage** and the acceleration and voltage

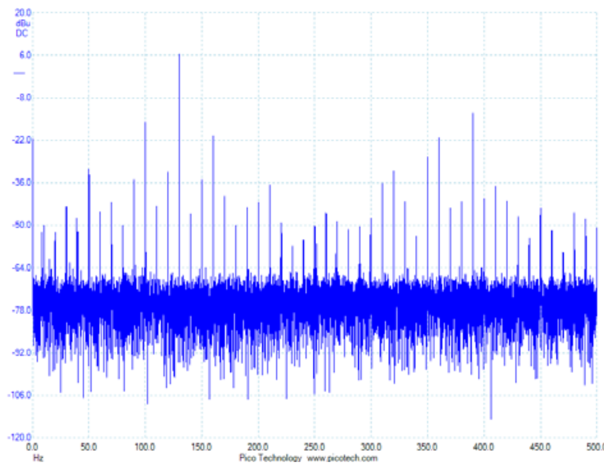


Figure 16 Result of Doppler laser vibration meter

d. Relationship of peak voltage and frequency

Test and measurement are done as describe before. The voltage of the test are normalized. The relationship of output voltage and exciting frequency are shown as Figure 17. The output voltage is peak value and the acceleration is 1g.

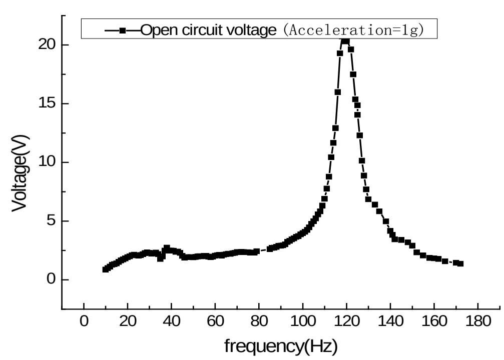


Figure 17 Relationship of peak voltage and frequency

It can be seen from Figure 17 that the output voltage will reach the peak value about 118Hz~119Hz. It is consistent with the ANSYS results. When the frequency of environmental excitation is deviate from the natural frequency of the piezoelectric energy harvester, the output voltage will decrease quickly.

e. Relationship between load resistance and frequency

When the external circuit are connect with different resistance, the power of the energy harvester will varied greatly. MIDE's Volture 25W bimorph are used shown in Figure 18, in which the piezoelectric bimorph are connected in series.

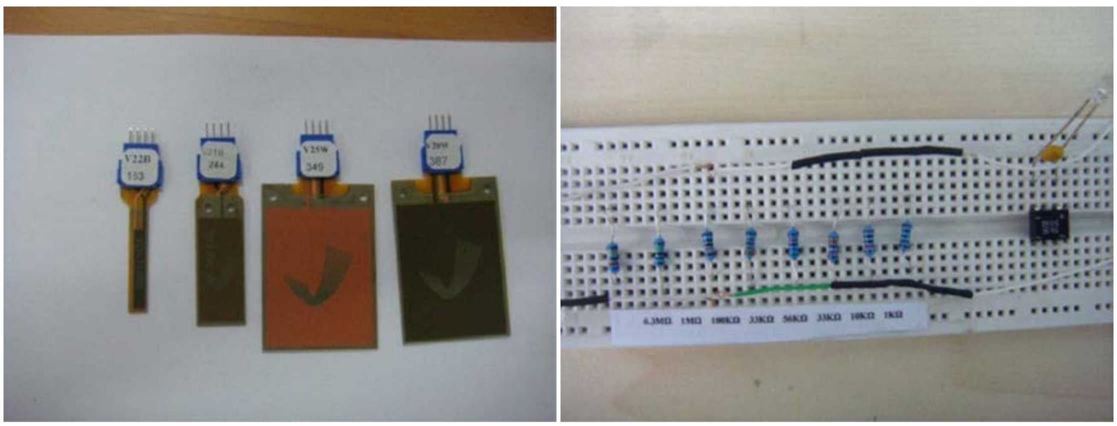


Figure 18 MIDE's Volture 25W and external resistance

When using a piezoelectric bimorph, piezoelectric bimorphs should be fixed on the fixture which installed on the shaker. Every voltage and acceleration of the piezoelectric energy harvester that correspondingly is recorded by the dynamic signal analyzer. After digital signal processing, the full frequency response curve of the device can be acquired as shown in Figure 19~Figure 22.

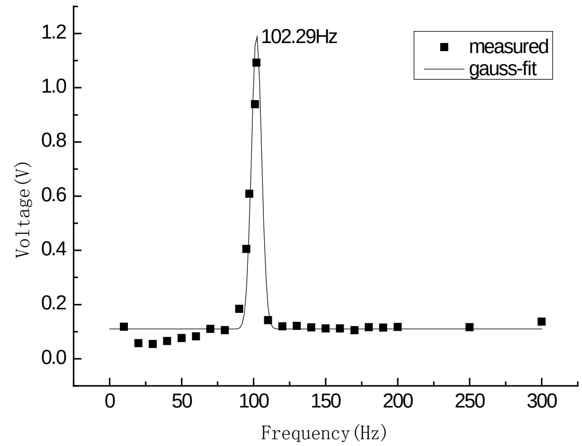


Figure 19 Frequency response curve(external resistor 1KΩ)

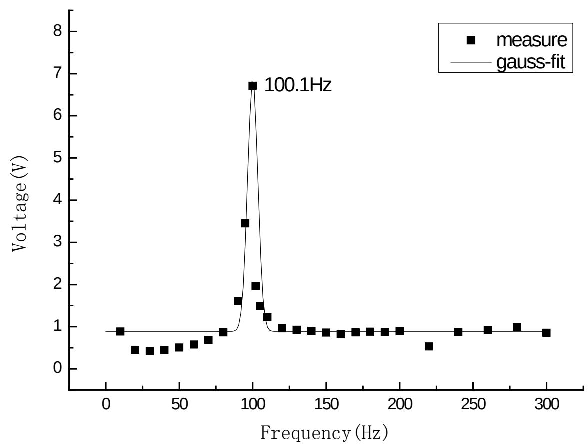


Figure 20 Frequency response curve(external resistor 10KΩ)

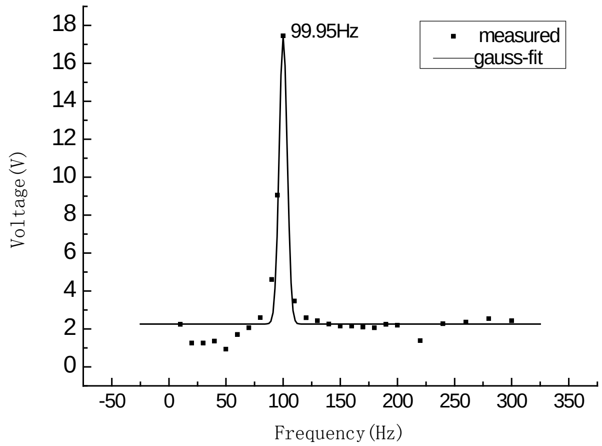


Figure 21 Frequency response curve(external resistor 100KΩ)

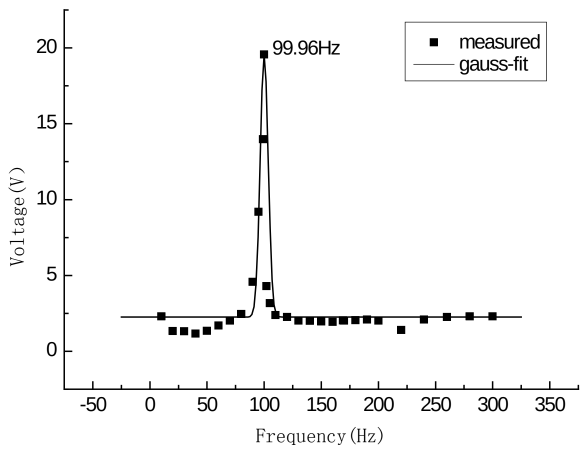


Figure 22 Frequency response curve(external resistor 1MΩ)

It can be seen from the test that with the increase of the external resistance, the voltage of the external circuit will increase too. But the increase will slows down when the external resistance is approach to the internal resistance of the energy harvester. On the other hand, the external resistance that connect in series will change the resonating frequency of the harvester, but the change is very little. Furthermore, when energy harvester is vibrating 100Hz on the shaker，the current of the circuit is measured by picoammeter after rectification respectively as the resistance is 1KΩ、10KΩ、100KΩ、1MΩ、6.3MΩ.The result is shown in Table.3.

Table 3.Current and power under different resistance

resistance (Ω)	1KΩ	10KΩ	100KΩ	1MΩ	6.3MΩ
Current(μA)	56.3	43.3	37.4	4.9	2.2
Power(μW)	3.18	18.7	139.9	24.01	30.49

Ⅹ.CONCLUSION

Geometry and shape parameters have great affect to piezoelectric single cantilever energy harvester. ANSYS and test are two powerful method to help to devise a high efficient energy harvester. External circuit parameters are also of great importance to the whole capability of energy harvester.

ACKNOWLEDGEMENTS

This work is supported by “Postdoctoral Foundation in Taiyuan University of Science and Technology (20142020)”, “PhD Foundation in Taiyuan University of Science (20132026)”, “Shanxi Undergraduate Training Program for Innovation and Entrepreneurship (2015272)” and “the Education Innovation Foundation for Graduate Students of Shanxi Province (2015023).

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