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Acceleration Magnitude and Resonance Frequency of Piezoelectric Micro Power Generator with Bridge Full Wave Rectifier Storage System

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Abstract
Piezoelectric Micro-Power Generator (PMPG) is a device used to convert mechanical vibration sources in the environment to an electric power via piezoelectric effects that could be used in specific applications. Experimental setup is conducted in this paper in order to test and study the PMPG capability of powering small device at low frequency applications with bridge rectification system. PMPG is tested with several acceleration magnitude of 0.2 g, 0.6 g, 0.9 g and 1.0 g .and the results shows inversely proportional relationship between the PMPG resonance frequency and its acceleration magnitude due to increasing the damping coefficients, Fabricated PMPG can deliver DC voltage to the final load of 2.21 V, DC current of 0.273μA and charge during one cycle equal to 8.27pC. Based on this results, the PMPG able to power large number of small electronic devices like cardiac pacemaker at low frequency and other medical implants.

Keywords: Acceleration magnitude, resonance frequency, piezoelectric micro power generator, bridge full wave rectifier storage system.

1. Introduction

Energy can neither be created nor be destroyed: it can only be transformed from one state to another. Energy conversion in macro level is popular since long time ago while in micro level still mature. Macro and micro energy harvesting are same in principle or theory but their applications are different.

Smart materials technologies and micro-electromechanical systems (MEMS) are mature, and become one of the most promising field in engineering in the last decade, because of very fast diminish of electronic device dimensions and its necessary power needed specially in remote area and medical implant.

Normal batteries such as lithium iodide are generally used as the power supply of electric energy. The short life span and high ratio of mass to electrical power for this traditional batteries. Also hazards and high cost of replacement for these batteries specially in medical implant application; motivates researchers and scientist for developing power harvesting devices.

At micro level there are more than one technique for power transform and harvesting such as electrostatic (Roundy *et al.*2002; Mitcheson *et al.*2004), electromagnetic (Williams& Yates1996; Glynne *et al.*2004; Arnold. 2007) and piezoelectric materials (Roundy *et al.*2003; Sodano *et al.* 2005; Jeon *et al.*2005). Piezoelectric technique has received much attention because of better electromechanical coupling and no external source needed, also for maximum power transfer from one type of energy to other many electrical and mechanical consideration must be taken into account.

In this paper we study the PMPG represented previous study (Alrashdan *et al.* 2017) in sensor and actuator mode, its study the relationship between the acceleration magnitude and output power produced and its resonance frequency, furthermore its measure the PMPG capability of replace lithium iodide battery along with the bridge rectification storage system.

2. Experimental procedure

Experimental procedure is carried out for model piezoelectric micro power generator cantilever beam based device discussed by [9] is done as following subsections.

2.1 PMPG Testing in Actuator Mode.

SEM is used to measure initial displacement of PMPG cantilever beam in absence of electrical load application. A laser displacement meter (LDM) keyence LC- 2420 shown in figure 1 is used to study the performance of our device in actuator mode. It used to measure the displacement of PMPG cantilever beam in very large frequency rang. LDM laser beam wavelength 670 nm is focused at center of proof mass located at cantilever beam free end. Initially, zero voltage applied to PMPG and the frequency is varied between 1 Hz to 1 KHz. The displacement amplitude is recorded based on the frequency of reflected laser beam from the vibrational PMPG cantilever beam and Doppler shift phenomena. PMPG quality factor can be determined based on the ratio between displacement for first and second resonance frequency. The maximum displacement normally occurs at first mode resonance frequency. LDM operating frequency affect the accuracy of PMPG displacement. In our frequency range, LDM system can measure displacement in nanometer range. Resolution of laser beam with spot size 20*12 µm at center of proof mass at cantilever beam free end is ± 0.01 micron. The most advantage of this LDM is that the vibration measurements can be done without any extra load added to device like in base shaking experiments.

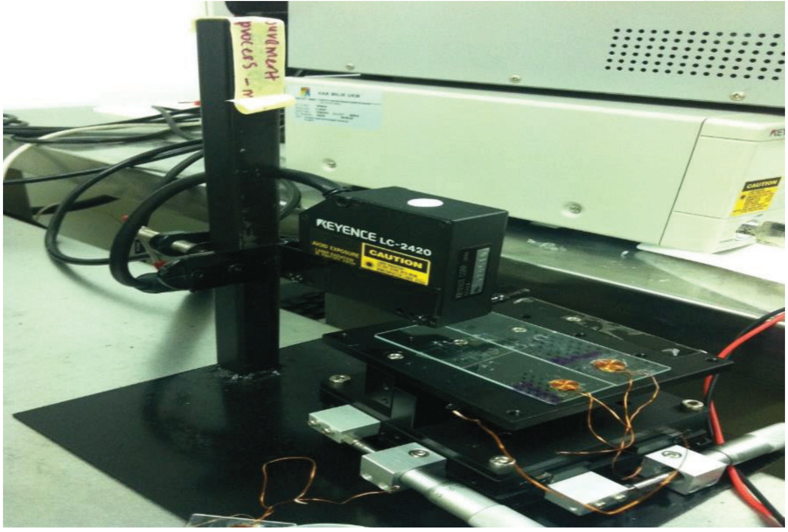


Figure 1. laser displacement meter (LDM) keyence LC- 2420.

The Agilent 4284A precision LCR meter shown in figure 2 and probe station is used to measure the relationship between applied voltage and resulting displacement at resonance frequency in actuator mode. The deformation is measured based on capacitance change between interdigitated electrode once the cantilever beam is bent upward or downward. As mentioned earlier, piezoelectric material not like other material and it's deform once electric field applied between electrode pairs. The capacitance between interdigitated electrode is varies based on cantilever beam displacement. Function generator is used to deliver voltage difference between interdigitated electrode at resonance frequency and Agilent 4284A precision LCR meter is used to measure voltage capacitance relationship between interdigitated electrode pairs. The voltage is varying between 1-33 V. and then the voltage displacement relationship of our PMPG is measured.

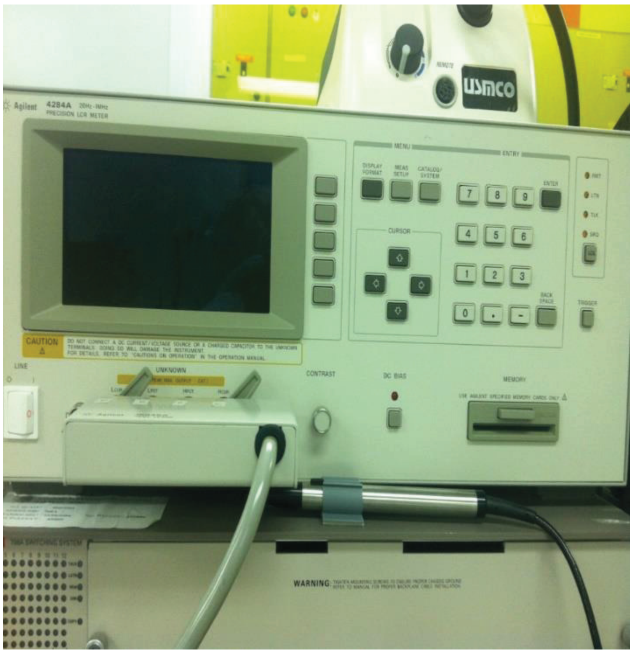


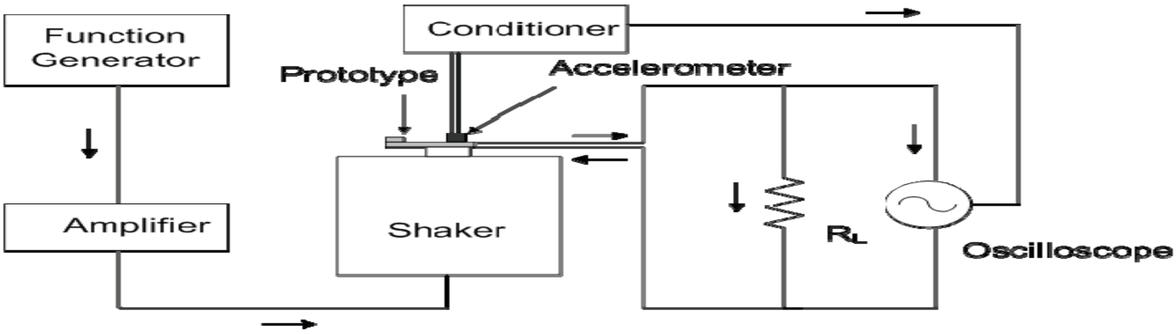
Figure 2 Agilent 4284A precision LCR

2.2 PMPG Testing in Sensor Mode

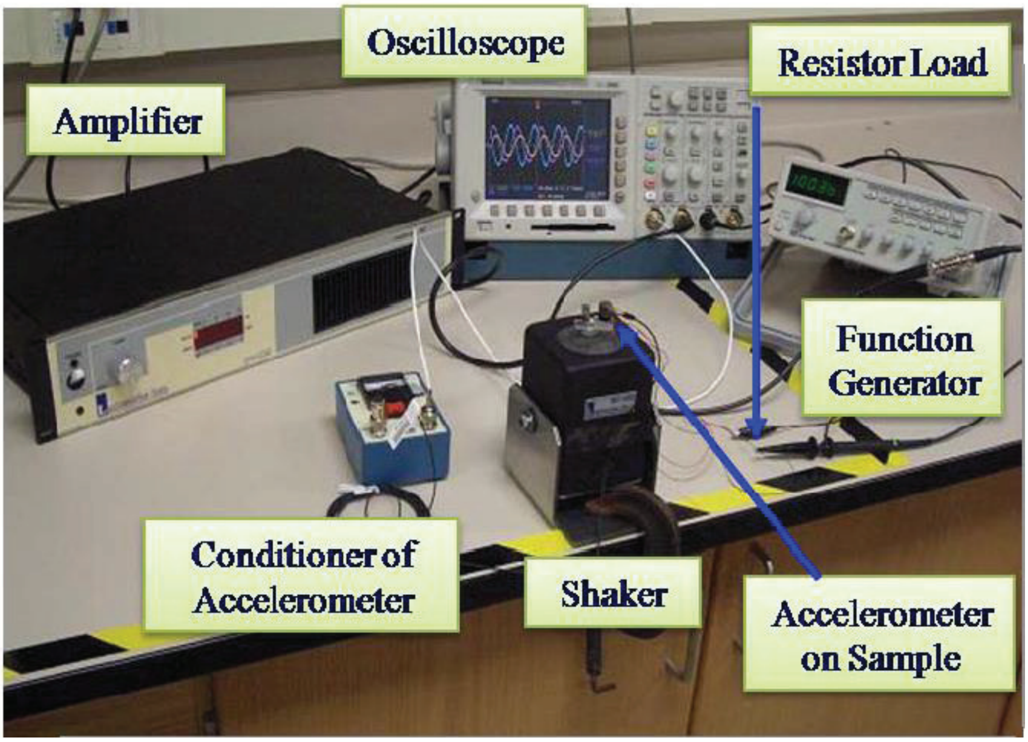
Base shaking experiment is used to study PMPG device in sensor mode. PMPG device is fixed at the top of DACTRON shaker, resistive load is connected to the positive and negative terminal of PMPG device , Osciloscope, Le Croy is used to measure output parameter at the resistive load .accelerometer connected to the shaker to control and measure the shaker acceleration magnitude ,the initial acceleration magnitude used in this procedure was 1.96 m/s2 or 0.2 g .the power is delivered to the accelerometer through conditioner .Function generator and amplifier connected in series used to derive the input sinusoidal wave signal to the shaker . The output voltage and power signals resulted from the resistive load and function generator are monitored on Oscilloscope. Input sinusoidal signal is applied at variable frequency range between 0-60 Hz. phase angle shifts between the input signal applied to the shaker and the resulting PMPG output are monitored, resonance frequency occurs when the phase shift angle between input and output signals are zero.

Under resonance frequency conditions. potentiometer or variable resistive load is used to evaluate the fabricated PMPG performance, where the maximum power deliver to the load when the load resistance equal to Thevenin equivalent PMPG resistance, the optimal load resistance was found by varying the load resistance between 50 KΩ to 9 M Ω and measure the PMPG output power.

After that, the optimal resistive load is used and the PMPG output voltage (V) , power (µW) are measured at frequency range varies again from 0-63 Hz at four different acceleration magnitudes (0.2 g , 0.6 g , 0.9 g and 1.0 g). Power density (µW/Cm3) is calculated based on PMPG output power and the volume of piezoelectric material used in resulting PMPG.



(a)



(b)

Figure 3. (a) Schematic diagram and (b) picture of experimental setup with a simple resistive load.

Micromanipulator probe station were used to study the relationship between external load applied and resulted voltage generated in PMPG in sensor mode. the first probe is used to deflect the cantilever beam and is positioned at center of proof mass, while the other two probes were connected to the positive and negative electrode to measure resulting voltage. Normal screw is used to apply the displacement at the center of proof mass, each revolution equal to 8 µm and each 90° angle revolution is equal approximately to 2 µm.

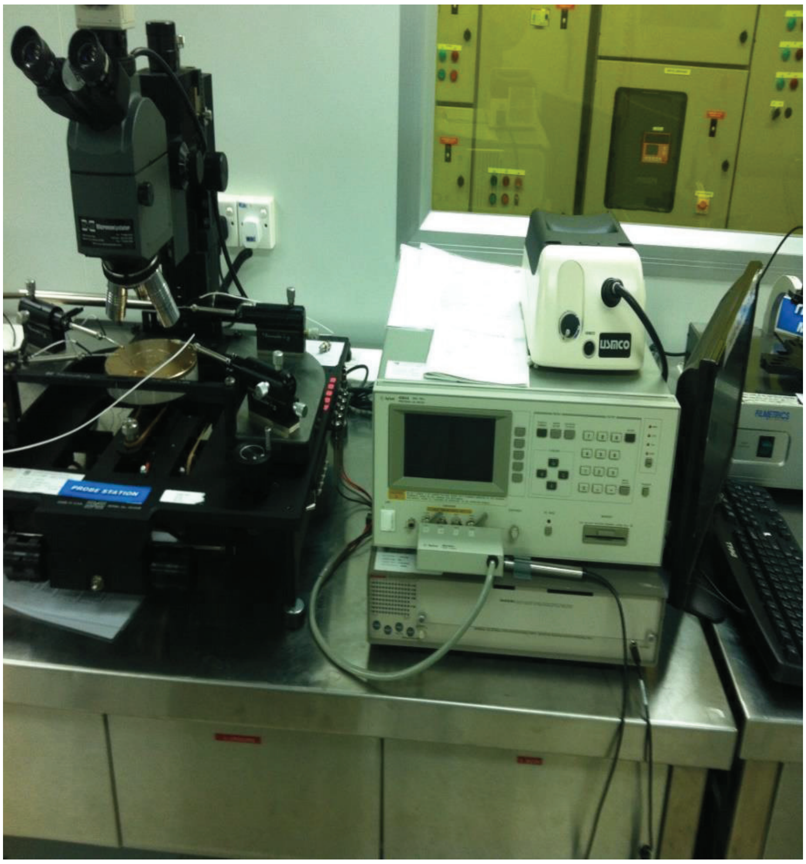


Figure 4. Micromanipulator probe station

2.3 PMPG Power Storage System

To measure how much DC voltage and current can PMPG deliver to final load or cardiac pacemaker .Full wave rectifier and filter is needed to convert AC voltage produced by PMPG to DC voltage to power cardiac pacemaker. The storage circuit consists of four Small Signal Schottky Diode LL42-GS18 Vishay Semiconductors with very low voltage drop during forward bias Vf =0.4 V and forward current level of 200mA. And 10 nf capacitor connected in parallel to 9MΩ resistor. As shown in figure 5 below. The PMPG device was shaken for 2.5 s at 33 Hz with acceleration magnitude of 0.2 g. The voltage across the load resistor equal to capacitor voltage since it's in parallel. The capacitor voltage is measured during charging and discharging periods once the shaker stop and the PMPG stopping deliver electric power to the load. The total current can PMPG supply is equal to current flow through 10 nF capacitor Ic plus current flow pass the load resistor IR.

$$I_R = \frac{V_R}{R} \tag{1}$$

$$I_C = C\frac{dV_C(t)}{dt} \tag{2}$$

$$I = I_R + I_c \tag{3}$$

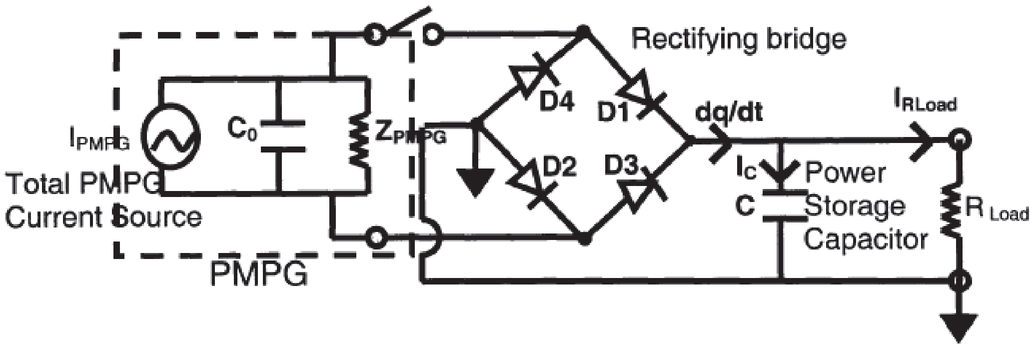


Figure 5. PMPG with bridge rectifier storage system.

3. Results and discussion

The data in figure 6 is taken from laser displacement meter (keyence LC- 2420) measurements. The maximum PMPG displacement occur at center of proof mass. At the beginning, the total displacement is kept around 0.5 µm and start suddenly to increase when the frequency 25 Hz and reach maximum displacement of 3.2 µm at 33 Hz which is the first resonance frequency mode and decreased sharply after that. The second and third mode of resonance frequency is, 254, 368 Hz respectively, the displacement at theses modes is negligible comparing with the first mode of operation. That's why I decide to consider the first resonance frequency as PMPG resonance frequency. The cantilever beam at 33 Hz is bend upward and downward not like the other mode which vibrate side to side. The PMPG quality factor in actuator mode equal to 64, which imply 64% of vibrational energy could transform to usable electric power.

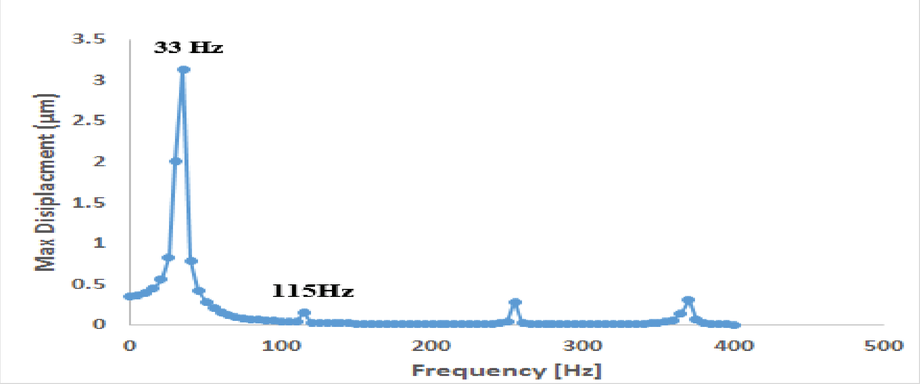


Figure 6. PMPG maximum displacement.

Figure 7 represent the approximately linear relationship between applied voltage and resulting maximum displacement when the voltage applied between 0-16 V , this linear relationship no longer available when the voltage higher than about 16 V , this is due nonlinear large electric field applied to Piezoelectric material and resulting nonlinear electric displacement and charge density ,also the resonance frequency is shifted and become smaller when voltage increased , this results will represent it in more details in sensor mode results . When the voltage varies between 0-33 v the R square value is 0.9547 which reflect very strong positive relationship between applied voltage and resulting maximum displacement in our fabricated MEMS PMPG device.

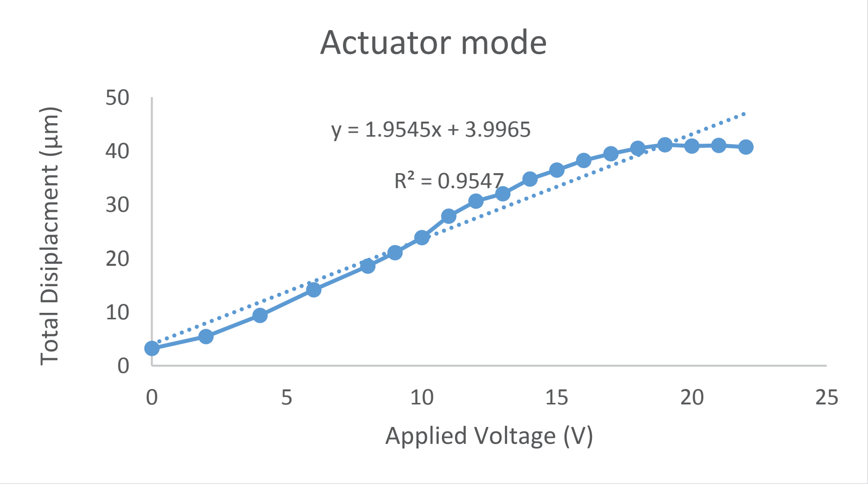


Figure 7. PMPG voltage – total displacement relationship in actuator mode.

At resonance frequency the phase angle shifts between input and PMPG output signal is zero as shown in figure 8. the two signal is out of phase when the running frequency is far away from PMPG resonance frequency. The phase shift is become smaller around resonance frequency and become exactly zero at resonance frequency 33 Hz which confirm the results carried in actuator mode. the simulated results show 26 Hz first mode resonance frequency while the fabricated device is about 33 Hz when the input signal acceleration of 0.2 g. The difference between simulated and fabricated frequency is 21%. Which reflect good design and fabrication procedure is toke place.

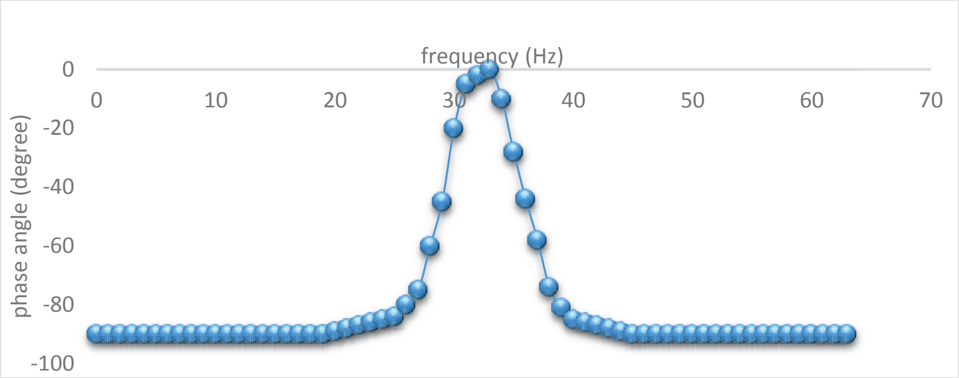


Figure 8. phase shift angel between PMPG input and output signals.

Figures 9 and 10 shows the optimal load resistance and output power at resistive load under resonance frequency, the output power is increased until the resistive load equal to 9 MΩ then decreased. while the output voltage is increased in linearly manner in this region with very strong correlation coefficient between variable resistance and measured voltage. The maximum PMPG output power is 1.7µW and corresponding peak voltage is 4 Volte. Figure 11 show the measured electric potential using 9MΩ resistive load and 33 Hz resonance frequency.

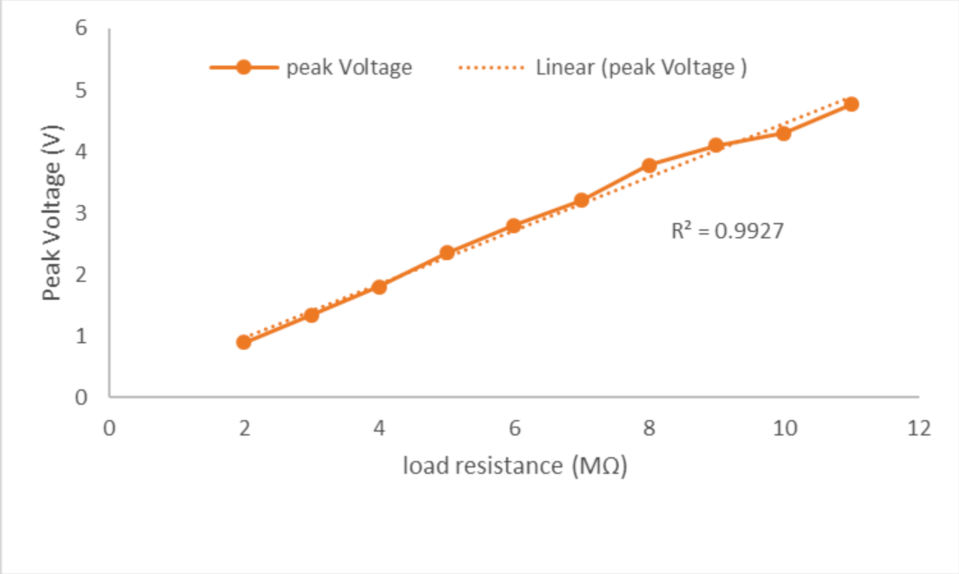


Figure 9: voltage across variable load resistance at 33 HZ.

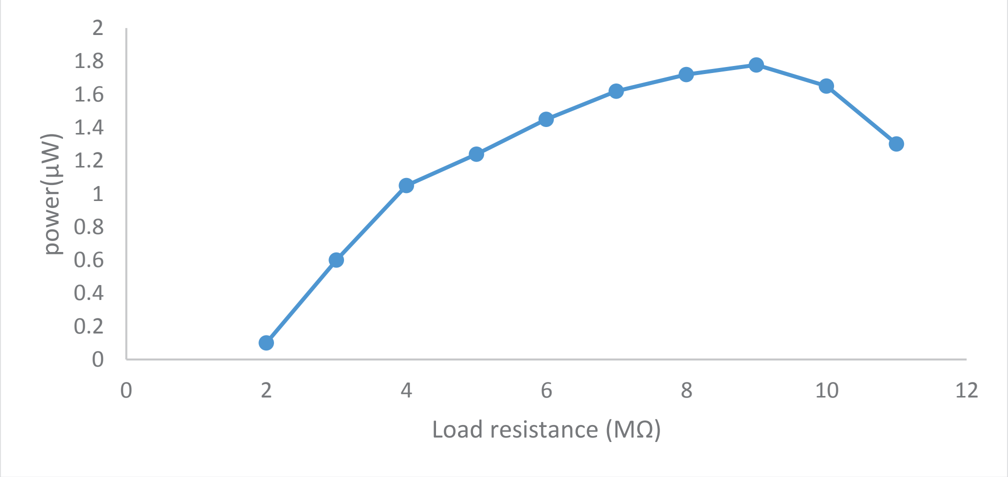


Figure 10: output power at viable load resistance at 33 Hz.

The resulting peak voltage, output power and power density is maximum at resonance frequency and is increasing with increasing input signal acceleration magnitude. The peak voltage or electric potential is measured at 9M Ω resistive load, 33 Hz and acceleration magnitude of 0.2 g is about 4 V as shown in figure 11. The output voltage signal is reached the steady state after 29 cycles and its takes about 0.9 sec to deliver steady state output voltage.

In Figures 12, 13 and 14. The PMPG output voltage (V), power (µW) and power density (µW/Cm3) is measured as a function of frequency, acceleration magnitude (0.2 g, 0.6 g , 0.9 g and 1.0 g).the resistive load is 9 MΩ. It's clear that there is positive relationship between the external load acceleration magnitude and resulting PMPG peak to peak voltage, output power and power density. In figure 12 the peak voltage increase from 4 v at acceleration magnitude of 0.2 g to12V when the external load applied acceleration magnitude is 1.0 g.

1.7 µW of PMPG output power increased to 9 µW when the acceleration magnitude increased from 0.2-1.0 g as shown in figure 13. the actual PZT layer volume in fabricated PMPG device is equal to 4(4mm* 160 µm * 1µm) +(0.79mm *0.94 mm * 1µm) =3.3026*10-6cm3. So the power density equal to 0.514W/Cm3 at acceleration magnitude equal to 0.2 g, and its increasing to 2.725W/Cm3 when the acceleration magnitude is 1.0 g as shown in figure 14. Which is very good enough to power cardiac pace maker? On the other hand, as shown in Figures 12, 13 and 14. The resonance frequency is decreased slightly once the acceleration magnitude increased due to nonlinear increasing of elastic compliance of PZT material with large acceleration magnitude and stresses applied. This results also clarify why the linear relationship between applied voltage and maximum displacement in actuator mode no longer available at higher voltage range and hence higher electrical stress induced to piezoelectric material. The relationship between PMPG resonance frequency and external load frequency is shown in figure 15.

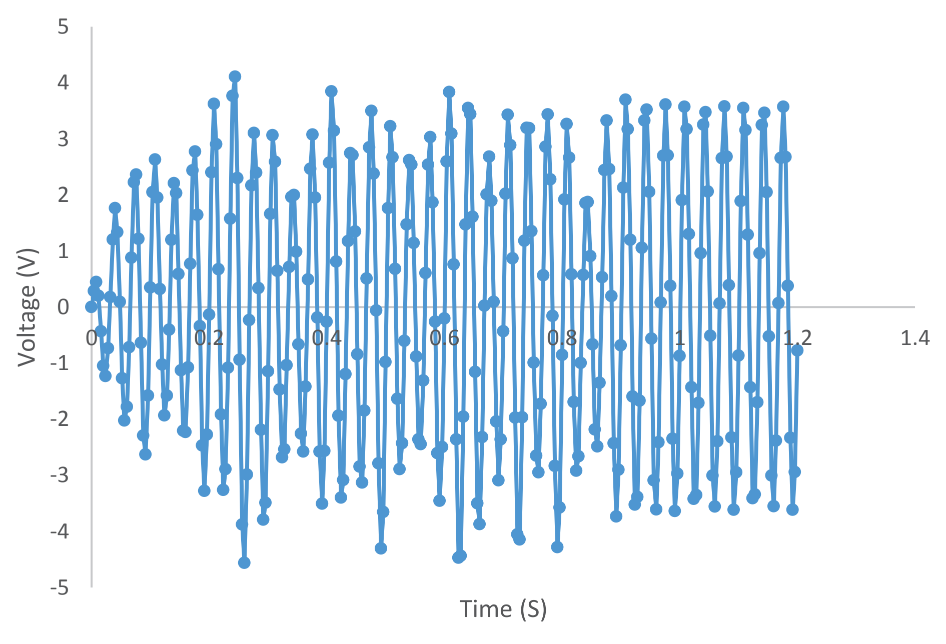


Figure 11. Output voltage at optimal load resistance vs. time.

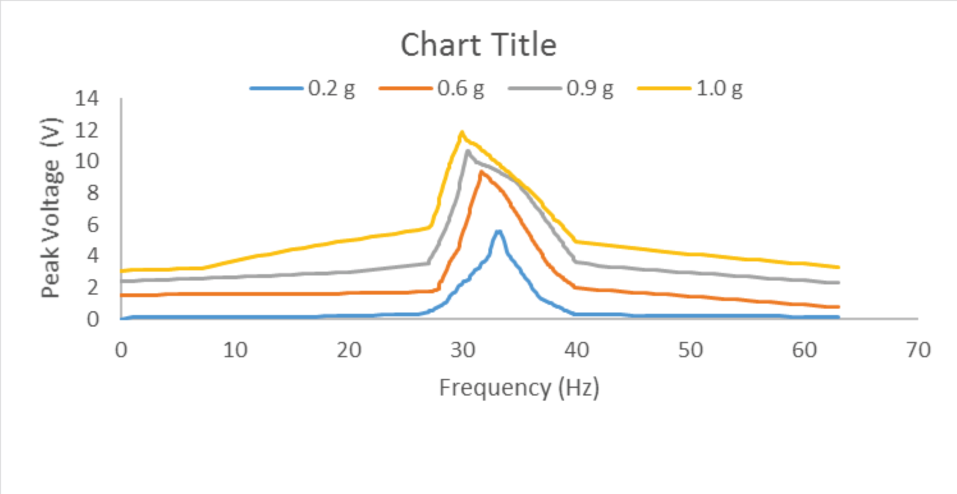


Figure 12: output voltage vs. frequency at different acceleration magnitude.

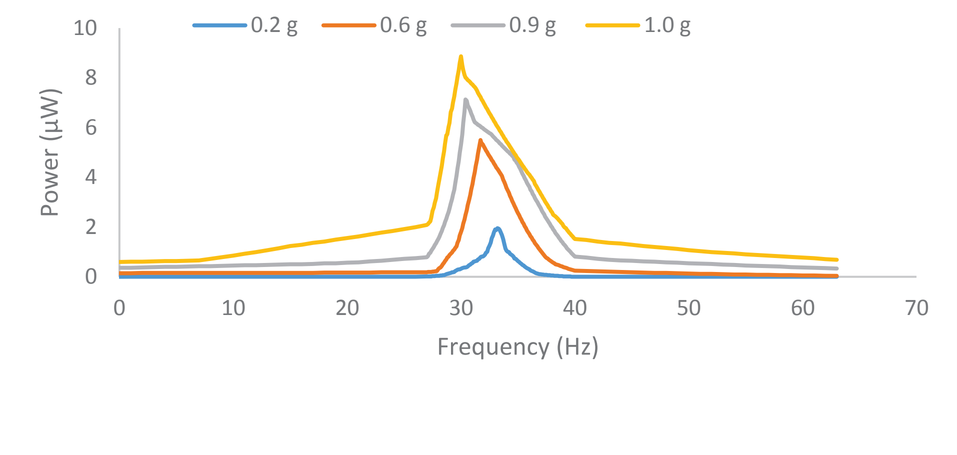


Figure 13: output power vs. frequency at different acceleration magnitude.

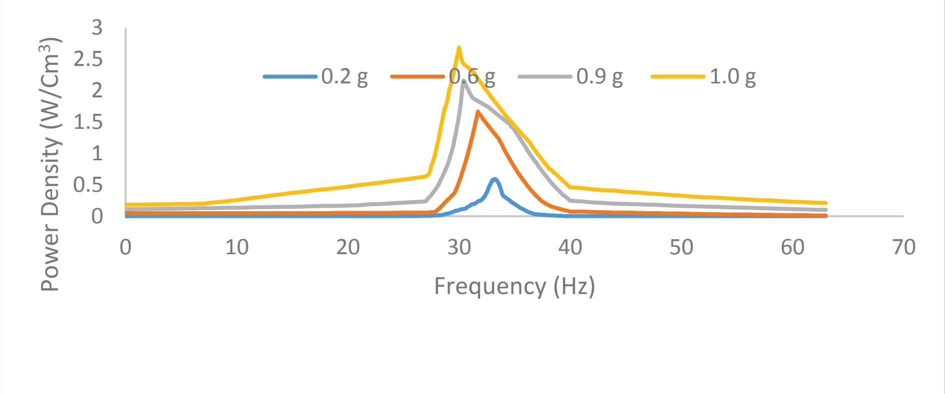


Figure 14: PMPG power density vs. frequency at different acceleration magnitude

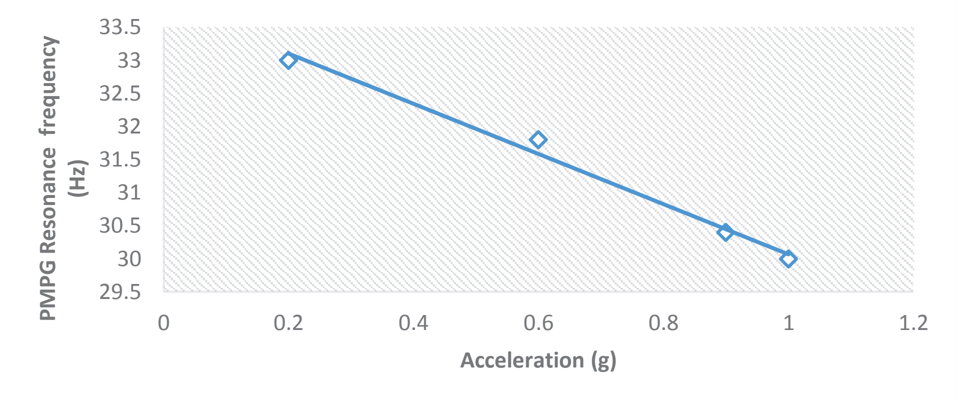


Figure 15: Relationship between PMPG first mode resonance frequency and acceleration magnitude.

Linear relationship between proof mass displacement and resulting voltage in PMPG in a sensor mode as shown in figure 16.

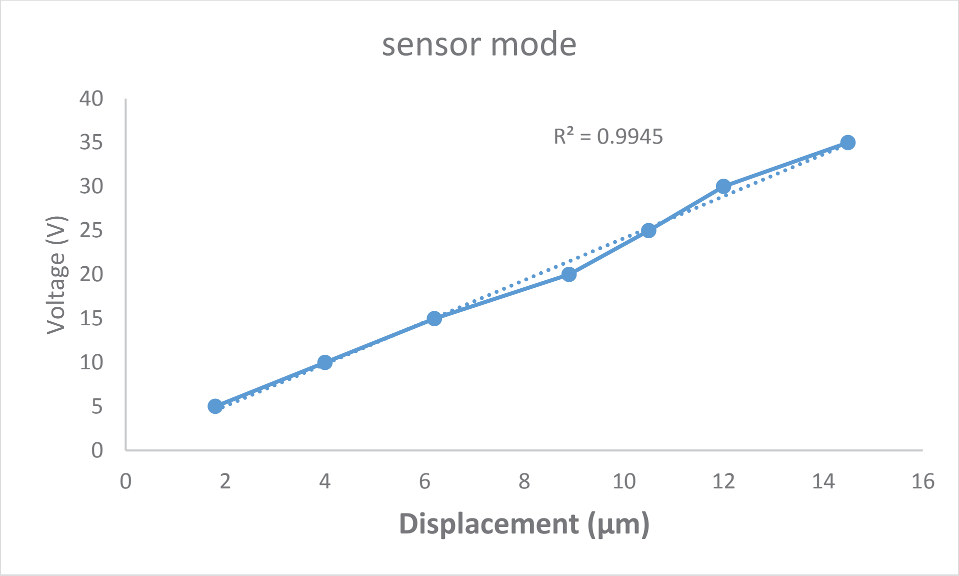


Figure 16: PMPG total displacement and voltage relationship in actuator mode.

In figure 17. Initially the capacitor voltage amplitude is very small once the shaker is not running. This voltage is due to initial displacement occur in the PMPG due to proof mass static weight. Once the shaker start running and PMPG start vibrate and voltage drop at capacitor is larger than 2 VF of the full wave bridge rectifier circuit even in forward or reverse bias. The capacitor start charging from time 7.98 s to 8.75 sec which is the rising time and is equal to 0.77 s. the rising time is approximately equal to 8 τ or 8RC = (8*9*106*10*10-9). The voltage is rising up exponentially during this period and reaching steady state DC voltage equal to 2.21 V. the theoretical root mean square voltage value (VRMS) or DC value is equal to (peak voltage -2VF / square root of 2. Or ((4-0.8)/1.4142= 2.26 v), the difference due to another voltage drop due to internal diode resistance. The charging period is started at 8.75s until 10.5 s which is equal to 1.75 s. this charging periods plus rising time period equal to 2.52 s which is the shaker running time. After the shaker is stop running the capacitor start to discharge within 0.9 s which is approximately equal to 10τ.

The corresponding capacitor current IC is approximately equal to 0.0223 μA is shown in figure 5.41. While IR equal to 0.251μA. so the PMPG can deliver a total Dc current of 0.273μA .and charge during one cycle equal to the total current flow multiplying with one period of time which is equal to 8.27pC.

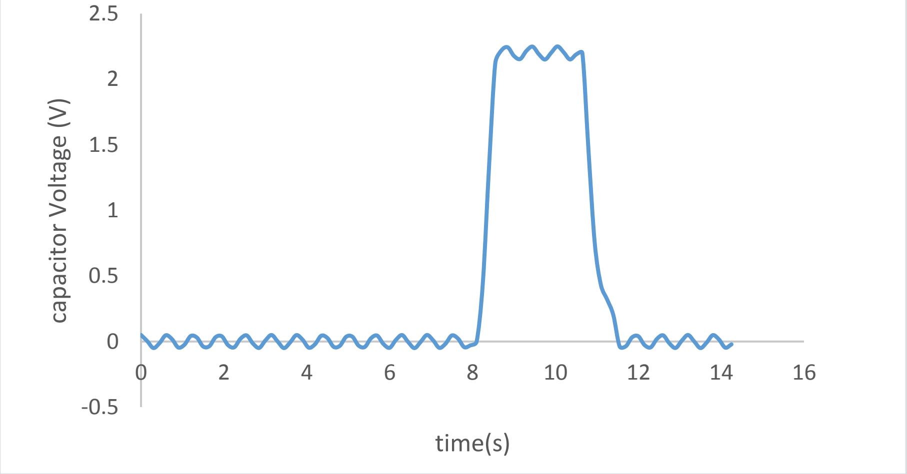


Figure 17 capacitor voltage during charging and discharging time.

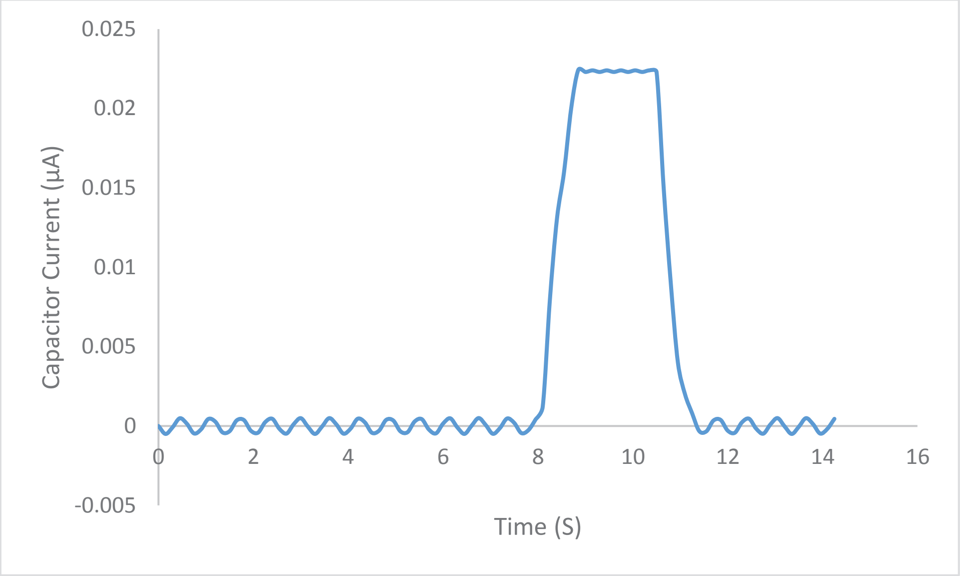


Figure 18. Capacitor current during charging and discharging time.

4. Conclusion

In this work, a PMPG is tested in sensor and actuator mode, and a proportional relationship between the acceleration magnitude and output power produced and power density is observed at its resonance frequency. On the other hand, inversely proportionally relationship between device resonance frequency and the acceleration magnitude applied.

In this paper Bridge Full wave rectifier and 10 nf capacitor connected in parallel to 9MΩ resistor used. Fabricated PMPG can deliver DC voltage to the final load of 2.21 V, DC current of 0.273µA .and charge during one cycle equal to 8.27pC. Based on this results, the PMPG able to power large number of small electronic devices like cardiac pacemaker at low frequency and other medical implants.

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