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Vibration Energy Harvesting Using Drum Harvesters

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Abstract

Piezoelectric circular diaphragm energy harvesters have been shown to perform well under high as well as low stress and a wide frequency range. This paper studies the performance of drum harvesters made using piezo buzzer elements under low stress and low frequency conditions. Drum harvesters of different sizes and steel ring IDs were fabricated and analysed for their electrical power harvesting capability under a dynamic force of 0.5 N in the frequency range of 30-300 Hz. A maximum DC output power of 2.463 mW was obtained with a 27mm drum harvester having steel ring ID of 24 mm across a load resistance of 27.4 kΩ at a resonant frequency of 213 Hz. A supercapacitor was charged using these harvesters and used to power a Arduino microcontroller board. The results show that these drum harvesters are capable of powering low power microelectronic devices using ambient vibrations from various sources.

Keywords— piezoelectric, drum harvesters, vibration energy harvesting, diaphragm, buzzer, LTC3588-2.

INTRODUCTION

Piezoelectric materials have been the centre of attention for researchers in the energy harvesting field for a few decades now. These materials have an inherent ability to convert mechanical stress or vibrations into electrical energy. Owing to their excellent electromechanical properties and ease of fabrication into various shapes and sizes and integrability into various structures and mechanisms, piezoelectric materials have grown in popularity. Hobbyists, inventors, enthusiasts and researchers alike have used piezoelectric materials in different structures like dance floors [1] and footwear [2-4] to demonstrate their energy harvesting capability. However, research into practicable and commercial applications has been focused towards powering wireless sensor nodes, acoustic systems, ultrasonic applications, structural health monitoring, etc. Lead Zirconate Titanate (PZT) piezoelectric ceramics have been the most popular piezoelectric materials along with PVDF and PMN-PT. In recent years, materials researchers have focused on fabricating better piezoelectric materials (lead free) with enhanced flexibility [5-7] and electromechanical properties.

With their power requirements falling manifold over the past decade, microelectronic devices and sensors today can be powered using energy harvesters. Table 1 [8-11] gives an overview of some low power microelectronic devices which can be powered by ambient energy harvesting.

TABLE.1. Low power microelectronic devices that can be powered using energy harvested from the environment

Device Name	Current Consumption
ICSENSE Smart power sensor interface chip	2.4μA
STM8L/STM32L microcontrollers	330nA(lowest power mode)
CC2640 bluetooth module	5.9mA/ 1μA standby
MN-31540SH GPS module	18 (track)/21mA(acquire)

Piezoelectric materials can be used to harvest energy in high stress as well as high vibration environments [12, 13]. Examples of high stress scenarios are tyre pressure in vehicles, heel strikes in human ambulation, etc. Vibrations are mostly encountered in and around machinery like heavy rotary machines, HVACs, air conditioners, refrigerators, etc. Most of the research carried out on piezoelectric energy harvesters has been with cantilever type harvesters [13-19]. For high stress applications, circular composite structures have been developed. Examples are moonie [13], cymbal [20] and drum harvesters [21, 22]. Moonie harvesters have been used in shoes where an energy output of 81 uJ or 81 uW per step and a power density of 56 uW/cm3 were reported [12]. Cymbal harvesters were investigated under high pre-stressed cyclic vibrations by Kim et al (20). They reported power levels of 33 mW and 52 mW under stress of 55 N and 70 N respectively at 100 Hz for a cymbal of dimensions 29 mm x 1.8 mm. Drum transducers and actuators were studied by Wang et al and Sun et al respectively [21, 22]. They reported a maximum output power of 11 mW at 590 Hz from a drum transducer having dimensions (20 x 1) mm^2. It was also found that deformation of the structure could be increased by changing the steel ring internal diameter [22].

Flexural composite discs or diaphragms have also been studied by researchers for their energy harvesting capabilities [23-27]. In this paper, the energy harvesting ~~capabilities~~ ability of drum harvesters under low stress has ~~have~~ been studied. Commonly available piezoelectric buzzer elements were used to fabricate drum harvesters of two different sizes viz. 35 mm and 27 mm.

Moreover, the circular diaphragm structure is commonly used for fabrication of sensors such as pressure sensors. Usually an external force applied on the pressure sensor stands for a long time [26]. From engineering mechanics, it is known that the highest stresses occur in the plane of a bent composite structure [27]. Owing to these reasons, circularly shaped piezoelectric energy harvesters are suitable for high/ low stress applications in a wide frequency range.

Drum harvesters work in the d$_{31}$ mode. The electrical/mechanical coupling for 31 mode is lower than for 33 mode. But the main advantage of operating piezo harvesters in the 31 mode is that the system is much more compliant, therefore larger strains can be produced with smaller input forces. Also, the resonant frequency is much lower [28].

Various ambient vibration sources can be used to harvest energy and power low power microelectronic devices like ~~and~~ ultra low power sensors and microcontrollers available today. These can be used for environmental monitoring, structural health monitoring, emergency backup power supply, emergency signalling and message transmission ~~etc~~. among a myriad of other applications. Table 2 [28] gives a list of ambient vibration sources.

TABLE.2. Ambient vibration sources

Vibration Source	**Acceleration (m/s^2)**	**Frequency (Hz)**
Car engine compartment	12	200
Base of 3-axis machine tool	10	70
Blender casing	6.4	121
Clothes dryer	3.5	121
Person nervously tapping their heel	3	1
Car instrument panel	3	13
Door frame just after door closes	3	125
Small microwave oven	2.5	121
HVAC vents in office building	0.2 – 1.5	60
Windows next to a busy road	0.7	100
CD on notebook computer	0.6	75
Second story floor of busy office	0.2	100

A comparison of various energy harvesting structures studied thoroughly by researchers is given in Table 3 [4, 12-13, 17-18, 21-27].

TABLE.3. List of energy harvesting devices.

Reference	**Device type**	**Power (mW)**	**Frequency (Hz)**	**Load at resonance (kΩ)**
Roundy [21]	Resonant cantilever	0.375	120	-
Sodano [22]	Resonant cantilever	1.5 - 2	0 - 250	1
Zheng [23]	Resonant cantilever	0.0325	150	98
Glynn-Jones [24]	Resonant cantilever	0.003	80	333
Marinkovich [25]	Resonant – Impulse driven	0.025	60	9200
Renaud [26]	Impulse driven	0.040	1	385
Leinonen [4]	Moonie	0.082	1	-
Kim [12]	Cymbal	39	100	400
Wang [13]	Drum transducer	1.1	590	18
Chen [17]	Circular diaphragm	12	113	33
Minazara [18]	Circular diaphragm	1.7	1710	5.6

EXPERIMENTAL PROCEDURE

Piezoelectric buzzers are available in various sizes. Commercially available piezo buzzers (Fig. 1) of 2 different dimensions (35 mm and 27 mm) were chosen for this study. Table 4 gives the dimensions of the piezo elements used. Steel rings (Fig. 2) of 3 different internal diameters (IDs) for each piezo element were fabricated using SS304 steel.

Fig. 1. **The piezoelectric buzzer elements**

Fig. 2. **The piezoelectric buzzer elements with steel rings**

The components were adhered using a commercially available synthetic rubber based adhesive (Fevibond). The adhesive was applied to both surfaces to be adhered and they were kept aside for about 10 minutes before joining them. The bonding achieved was excellent and at no time during the experiments was any structural disintegration noticed. Wires were soldered on the central piezo disc and on the metal substrate at the periphery to act as leads. Figure 3 shows the drum harvesters fabricated. Table 4 gives the details of the dimensions of the components used. Fig. 4 shows the experimental setup.

Fig. 3. **The drum harvesters**

TABLE.4. Dimensions of the piezo buzzer elements used to make drum harvesters

Diameter of metal substrate (mm)	Diameter of piezo disc (mm)	Thickness of metal substrate (mm)	Thickness of piezo disc (mm)	Steel ring ID (mm)
27	20	0.20	0.20	23, 24, 25
35	25	0.25	0.25	33, 34, 35

Fig. 4. **The experimental setup**

A d33 meter (Piezo–test PM300) was used as the excitation mechanism for the drum harvesters. A maximum sinusoidal dynamic force of 0.5N could be applied using this setup. The frequency range was 30 – 300 Hz. The drum was fixed to the holder of the d_{33} meter using insulated circular clamps provided with the device~~ as shown in figure 3b~~. The diameter of the clamps was 10 mm.

The AC voltage output of the drum harvester was monitored and recorded using a digital oscilloscope (Agilent DSO 1052B). The AC voltage was converted into DC using a conventional bridge rectifier circuit employing 1N5819 schottky diodes across which a capacitor of 470 µF was added. The power deliverability of the drum was measured by connecting a current source (Keithley 6221 DC and AC current source) working in sink mode acting as a resistive load in parallel with the output capacitor. Fig. 5 (a ,~~&~~b) ~~6~~ gives the schematic and photo of the circuit used.

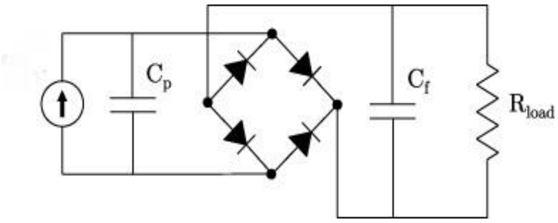

Fig. 5. **a) Circuit Schematic**

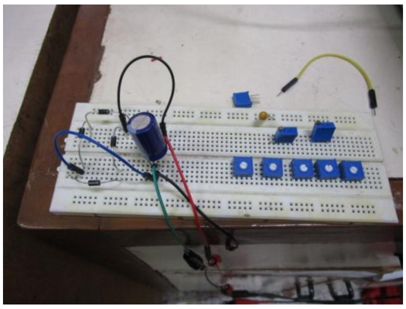

Fig. 5. **b) Circuit on breadboard**

The current sinking capacity of the current source acting as a load was varied and the corresponding output voltage was recorded. Short circuit current and open circuit voltage delivered by the drum harvesters were measured.

The voltage developed across the output capacitor was measured using a nano voltmeter (Keithley 2182A). The load resistance value was calculated by dividing the voltage across the output capacitor by the current.

RESULTS AND DISCUSSIONS

The analysis was done with samples in triplicate that is 3 samples for each configuration. Fig. 6 (a to f) shows a plot of the AC output voltage (V_{OC}) as a function of the frequency (F) for different steel ring IDs.

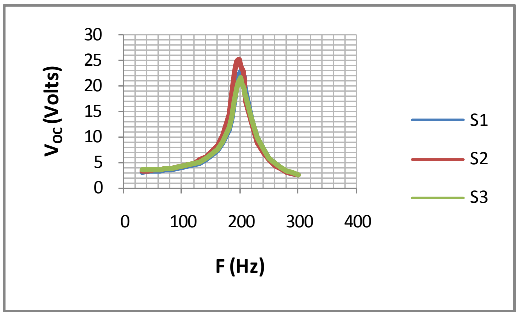

Fig. 6. **a) 35mm drum with steel ring ID 33 mm**

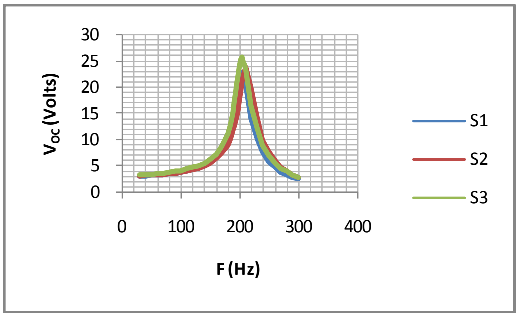

Fig. 6. **b) 35mm drum with steel ring ID 32 mm**

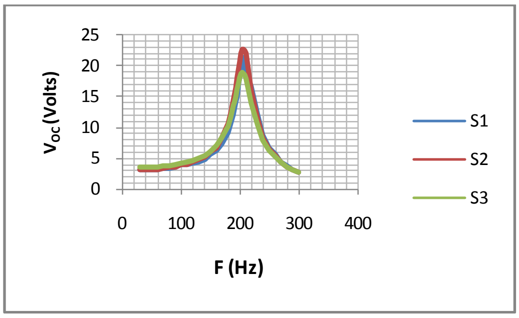

Fig. 6. **c) 35mm drum with steel ring ID 31 mm**

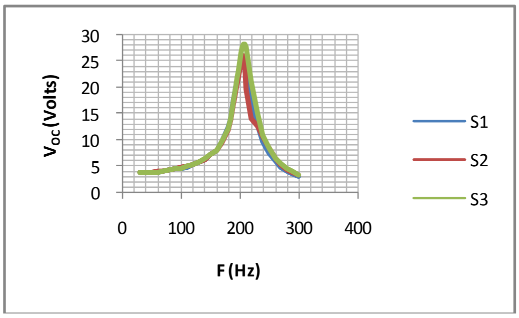

Fig. 6. **d) 27mm drum with steel ring ID 25 mm**

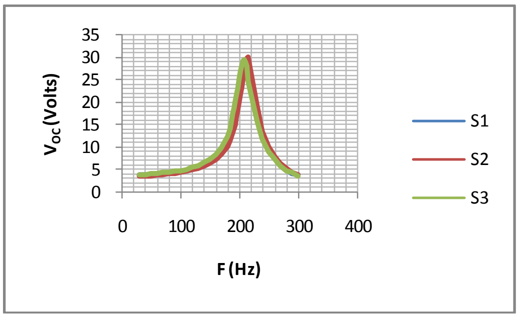

Fig. 6. **e) 27mm drum with steel ring ID 24 mm**

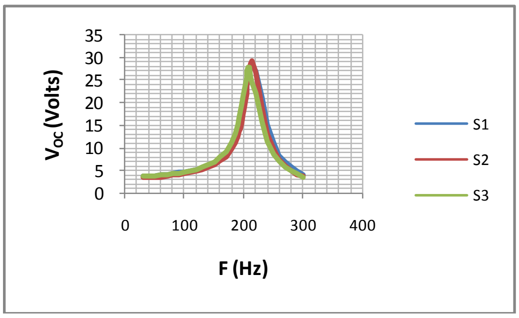

Fig. 6. **f) 27mm drum with steel ring ID 23 mm**

As is evident from the plots in Fig. 6, the output voltage increases with frequency, reaches a peak at resonance (for the given excitation profile) and then decreases. Also, the peak voltage values were highest for the 35 mm drum with steel ring ID 32 and in the case of the 27 mm drum peak voltage was observed for the steel ring ID of 24 mm.

The DC power (P) vs. resistive load plots for different steel ring IDs are shown in Fig. 7 (a to f).

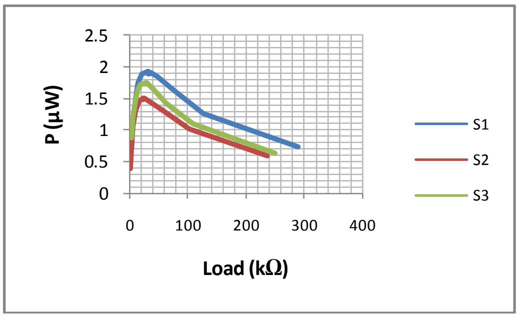

Fig. 7. **a) 35 mm drum with steel ring ID 33 mm**

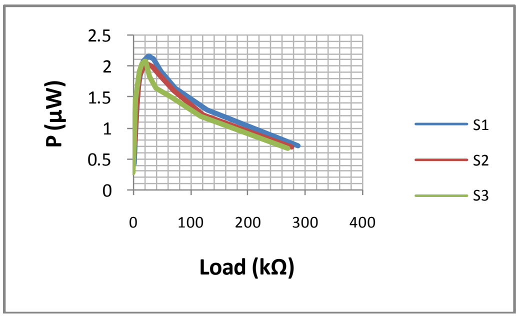

Fig. 7. **b) 35 mm drum with steel ring ID 32 mm**

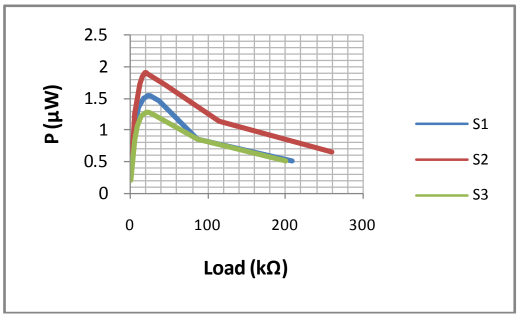

Fig. 7. **c) 35 mm drum with steel ring ID 31 mm**

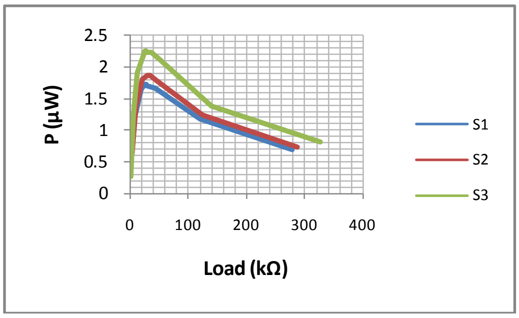

Fig. 7. **d) 27mm drum with steel ring ID 25 mm**

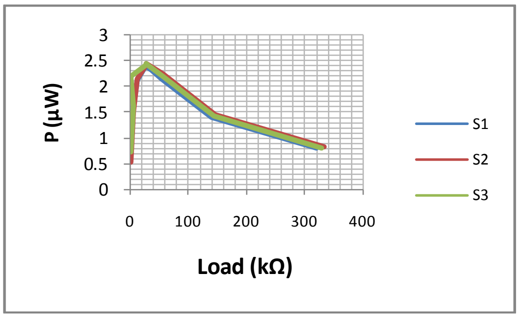

Fig. 7. **e) 27mm drum with steel ring ID 24 mm**

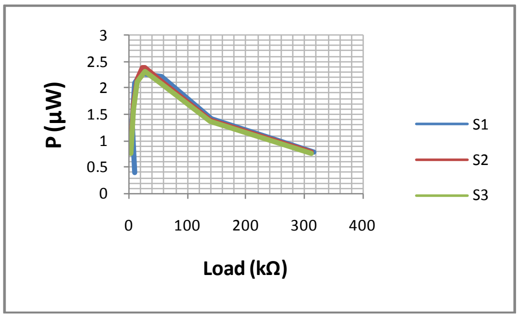

Fig. 7. **f) 27mm drum with steel ring ID 23 mm**

TABLE.5. Load resistance, peak voltage and peak power of the drum harvesters at resonance.

Drum OD (mm)	Steel ring ID (mm)	Sample No.	Resonance Frequency (Hz)	V_{AC} (volts)	V_{DC} (volts)	Peak Power (mW)	Load (kΩ)
35	33	S1	205	29	14.5	1.932	30.93
35	33	S2	205	33.2	16.49	1.504	24.29
35	33	S3	203	27.6	13.77	1.752	28.26
35	32	S1	206	33	16.64	2.142	23.80
35	32	S2	211	30.2	15.23	2.037	22.63
35	32	S3	209	30.4	15.2	2.092	21.10
35	31	S1	206	26.2	13.1	1.537	21.72
35	31	S2	210	29	14.67	1.918	19.33
35	31	S3	204	23.2	11.62	1.273	22.14
27	25	S1	207	32	16.19	1.725	25.62
27	25	S2	213	33.2	16.75	1.870	29.92
27	25	S3	210	36.2	18.5	2.259	26.88
27	24	S1	216	37.4	18.68	2.379	28.31
27	24	S2	214	37	18.76	2.447	27.08
27	24	S3	213	37.4	19.02	2.463	27.40
27	23	S1	215	38	19.03	2.332	25.50
27	23	S2	219	35.8	17.95	2.384	23.00
27	23	S3	215	35.4	17.76	2.321	25.82

Table 5 lists the dimensions of the drums, their resonance frequencies, peak power and the electrical load at resonance for all the samples tested. As can be seen, for the 35 mm drum, a steel ring ID of 32 mm gave maximum peak power indicating that the optimum ring ID is around 32 mm. For the 27mm drum, the maximum peak power was obtained at a ring ID of 24 mm similarly indicating that the optimum ID is around 24 mm.

The resonance frequencies of the drum harvester samples ranged between 200 and 220 Hz. A maximum dynamic force of 0.5 N could be applied with the setup used.

The load resistance at resonance is in the range of 20-30 kΩ which means that low impedance devices can be powered using these energy harvesters. Previous research [12, 21-26] has reported high matching loads with power output mostly in the microwatt range.

Further, the 27 mm drums were able to generate more power compared to the 35 mm drums. This may be attributed to the fact that the contact area of the clamps used to apply the force was greater for the smaller drum harvesters. Hence an analysis also needs to be done on the effect of contact area on power output.

Pre-stress has been shown in previous literature (13) to increase the power output and at the same time lower the resonance frequency of drum harvesters. Due to unavailability of suitable instruments, pre-stress analysis could not be conducted. Future work will incorporate effect of pre-stress on the power output and resonance frequency.

The aforementioned drum harvesters of various dimensions were operated at resonance and used to charge a supercapacitor (Cornell Dubilier ~~rated at~~ 0.1 F/5.5 V) ~~upto~~up to 5volts. A 5V zener diode was used to regulate the charging voltage. Fig. 8 (a, b) shows the charging curve of the capacitor charged ~~upto~~up to 5 volts.

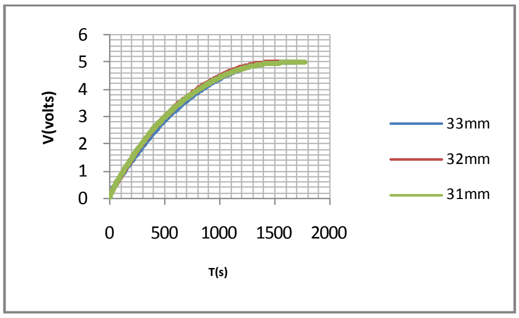

Fig. 8. **a) Charging with 35 mm drum and 3 different steel ring IDs**

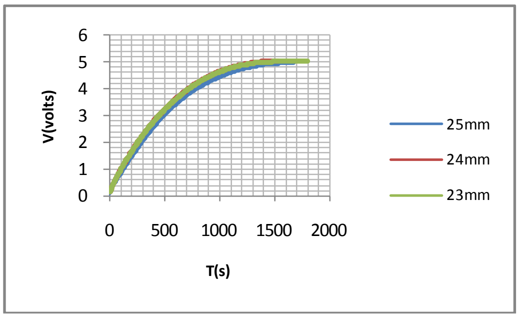

Fig. 8. **b) Charging with 27 mm drum and 3 different steel ring IDs**

The time required to charge the supercapacitor to 5 V with different drum harvesters is given in Table 6.

TABLE.6. Supercapacitor charging with drum harvesters

Drum size (mm)	Steel ring ID (mm)	Charging time (min)
35	33	26
35	32	24
35	31	28
27	25	26
27	24	23
27	23	35

It can be inferred from Table 6 that the drum harvesters with the optimum steel ring ID charge the supercapacitor faster indicating greater energy generated per unit time. The energy stored in the supercapacitor upon reaching 5 volts ~~is~~ $=1/2CV^2 = 1/2 \times 0.1 \times 25 = 1.25$ J. Also, the 27mm drums had a faster charging time as compared to the 35 mm drums which may be due to the reason mentioned earlier.

The charged supercapacitor was successfully used to power a Arduino microcontroller board (Fig. 9). The Arduino board was first loaded with a basic program to flash an on-board LED, using a PC. Then it was disconnected from the PC and powered using the supercapacitor charged up to 5 volts. The microcontroller was able to execute the flashing LED program for about 10 seconds powered only by the supercapacitor. As the voltage of the supercapacitor fell below 3volts, the flashing stopped. This can be attributed to the minimum voltage required to power the Arduino board.

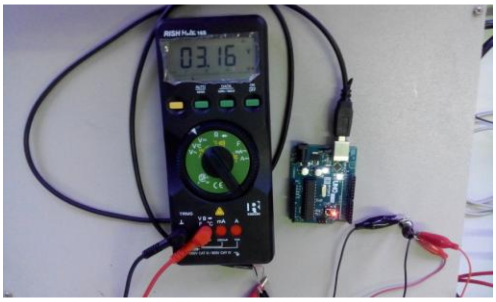

Fig. 9. **Arduino board powered by the supercapacitor**

A commercially available energy harvesting IC LTC 3588-2 was also used for harvesting energy from the drum harvesters. Fig. 10 (a, b) [29] gives the schematic and photo of the circuit

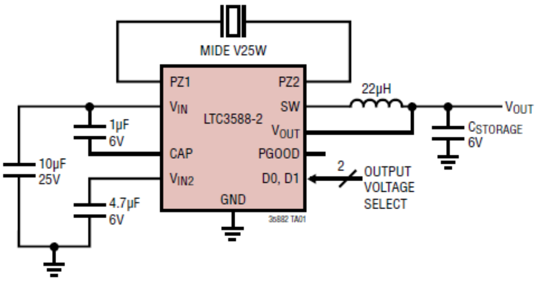

Fig. 10. **a) Arduino board powered by the supercapacitor**

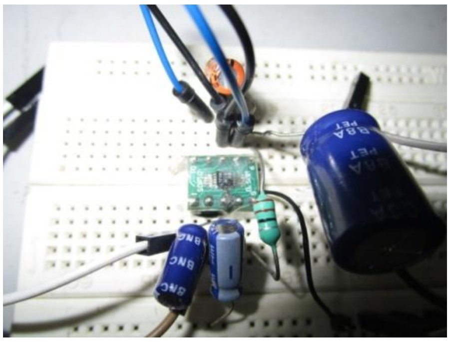

Fig. 10. **b) Arduino board powered by the supercapacitor**

The energy harvesting IC was mounted on a PCB and tested with regular electronic components on a breadboard as SMD parts were unavailable. It was able to deliver a constant DC output of 5 volts. The power delivered was calculated using the same setup as earlier and it was found to be 1 mW. It could deliver a maximum current of 0.2 mA which was measured using the current source in sink mode. However, as the current sinking increased beyond 0.2 mA, the output voltage of this circuit dropped rapidly below 5 volts and the circuit failed to regain a constant output even after disconnection of the load. Further analysis needs to be done to troubleshoot this problem and we believe this energy harvesting IC will be suitable for powering microelectronic devices up to the 1 mW range using the drum harvesters.

CONCLUSION

Drum harvesters were fabricated using commonly available piezo buzzer elements. The IDs of the steel rings used to make the drum harvesters were varied and an optimum ring ID was found which generated the highest power. It can be further optimized.

A maximum power of 2.463 mW was obtained with the 27 mm drum having steel ring ID of 24 mm. Compared to the 35 mm drum harvesters, the 27 mm drums were able to generate more power. This may be due to the contact area of the clamps used to apply the force. The effect of contact area on output power will be studied in the future.

These drum harvesters are suitable for high stress applications. Therefore, future work will also incorporate a study on effect of pre-stress on power output and performance under high cyclic stress conditions. Preliminary investigation with mechanical preloads has revealed that the resonance frequency can be reduced to as low as 27 Hz.

The fabrication process of these drum harvesters is cheap, easy and fast. They are quite robust and as such may be embedded in a variety of structures like shoes, under floors, roads, etc. to generate useful electrical energy which can be used to power microelectronic devices like Bluetooth, GPS modules, microcontrollers and low power sensors.

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