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Vertical Vibration based Electret-Cantilever Method of Micro-Power Generation for Energy Harvesting

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Abstract*— Energy harvesting is a process that captures small amounts of energy that would otherwise be lost as heat, light, sound, or vibration. This paper presents the fabrication, set up, experimental operations and output characteristics of a vertical vibration based electrostatic micro-power generator for harvesting ambient vibration energy from the environment. A vibration based cantilever-electret micro energy harvester was set up whereby an electret was used as an electrostatic inducing generator; and the fabrication of the upper electrode was carried out in the form of a T-shaped cantilever from materials of copper with embedded glass epoxy. Vertical vibrations of the cantilever in non-contact mode; and close to contact mode of operation were investigated. Maximum output power was realized towards the contact point of both the upper and the lower electrodes, after which there was distortion of signals. The maximum output power in close to contact mode of operation that was realized with electret surface potential of -171V was about 48nW.

***Index Terms*—Cantilever, Electret, Energy Harvesting, Micro-power generation.**

I. INTRODUCTION

Increasing energy demands are continuously leading to more energy harvesting technology research that are engineered towards unlimited power supply to operate wireless electronics, portable devices, stretchable electronics, wireless sensor networks (WSNs), micro electromechanical systems/nano electromechanical systems (MEMS/NEMS) devices and implantable biosensors. Energy harvesting or energy scavenging is a process that captures small amounts of energy that would otherwise be lost as heat, light, sound, vibration or movement. This captured energy can be used to power new technologies such as WSNs, MEMs and NEMS devices, and other handheld devices. Micro-power generation describes the development of very small electric generators or devices to convert heat or motion to electricity, for use close to the generator [1]. These devices offer the promise of a power source for portable electronic devices with very light weight, and have a longer operating time than existing batteries. Energy harvesting is a potential alternative power supply that will outlast its application [2]. Some of the benefits of energy harvesting among many others are: long lasting operability, no chemical disposal, cost saving, safety, maintenance free, no charging points, inaccessible sites operability, flexibility, and applications otherwise impossible; like wearable/implantable devices and stretchable electronics devices. Recently, much attention has been drawn towards devices that can harvest vibration energy from the environment and have the potential to replace batteries in these handheld devices or WSNs [3], [4]. Vibration energy harvesting is a potential unlimited power source to MEMS/NEMS devices. Vibration energy harvesters have the promises of long-lasting power sources as alternatives to existing batteries. Mechanical energy in the form of vibrations is commonly available in low frequencies up to 100Hz, and can be converted into electrical forms by means of energy harvesting techniques [5], [6]. The choice of a specific transducer mechanism for energy harvesting from vibration is heavily dependent on both the operating conditions (amplitude, and frequency spectrum of the excitation vibration which must be very low for this application), and the available space given by the application environment (which should be small in size) [7]. There are three major techniques that can be used to generate electricity from vibrations; electromagnetic (inductive), piezoelectric, and electrostatic (capacitive) methods of generation. Most of published works were focused on electromagnetic and piezoelectric approaches, and some are presented in [7] – [14]. The electromagnetic approach is most efficient at large power plants since scaling laws show them to be superior at large sizes. An electromagnetic method usually employs the means of a mass mounted on a spring which vibrates relative to the housing when subjected to an external vibrational force. The mechanical energy of the moving mass would then be transformed to electrical energy by having the mass move a magnet relative to a coil. However, with this arrangement, the effect of resonating frequency for electromagnetic method of vibration energy harvesting cannot be overemphasized. In a similar way, harvesting ambient energy by means of piezoelectric method necessitates the design of ultra-low power logic circuits, and an efficient power delivery interface circuits that can extract the maximum power available out of the energy harvesters. Also, the power consumed in the control circuits of these harvesters reduces the amount of usable electrical power. In recent times, there has been effort geared towards the use of the electrostatic approach of harvesting vibration energy. Also, electret-based electrostatic method with vibration in the horizontal plane (in-plane) is becoming common with some discussed in [3], [15] – [19]. Work on cantilever-

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electret based electrostatic micro-power generator with vibration in the vertical plane is not yet common, and for the available ones, they involved non-contact mode of operation [20]. The concept of cantilever-electret based electrostatic micro power generator is illustrated in Fig. 1. An electret dielectric with air or other medium is placed between two plate electrodes as shown in the figure. The electret is attached to the lower electrode (base electrode) while the upper electrode (counter electrode) is allowed to vibrate freely either horizontally or vertically. An electret behaves like a battery or acts as an electrical equivalent of a permanent magnet. An electret is a stable dielectric material with a quasi-permanently embedded static electric charge or dipole polarization which, due to the high resistance of the material, will not decay for a long period of time. Free charges are deposited on the electret by external charging and when placed in the arrangement shown, charges are induced to the upper electrode and there is transport of charges if connected to an external load due to changes in the capacitance between the two electrodes caused by movement of the upper electrode.

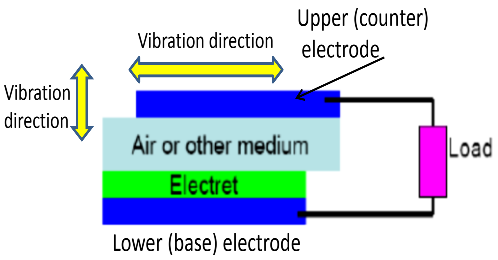

Fig 1 Basic concept of cantilever-electret based electrostatic micro power generator (adapted from [4]).

For electret power generators, the challenging issue is that they do require careful gap control between the two electrodes; otherwise, they lose performance greatly [21] - [23]. This stems from the fact that power output depends on the capacitance between the two electrodes. Electrostatic attraction force in the vertical direction increases with decrease in the gap between the electrodes, therefore gap control is crucial to avoid pull-in. For these reasons, most previous works on MEMS using electret-cantilever arrangement for energy harvesting has been mainly with a fixed distance between the electrodes and vibration in the horizontal plane; and effort to maximize power is geared towards optimal design of the shape of the plate electrodes. Different materials have been examined in the past as electret; ranging from materials of waxes, polymers, or resins [24]. Cyclic Transparent Optical Polymer (CYTOP), a per fluoronated amorphous (non-crystalline) polymer with ultra-high light transparency levels greater than 95%, which was developed by Asahi Glass Company Limited [25], can also work as an electret material. It has been demonstrated to be a better electret material with higher charge density and has been used by some researchers [3], [20] – [23]. Attractive properties of this polymer include high thermal stability, low dielectric constant, low water absorption, and excellent chemical resistance. Also, since it is a thermoplastic, it lends itself well to extrusion coating. CYTOP also maintains a low refractive index, low coefficient of optical dispersion, and good lamination properties. This, coupled with its thermoplastic characteristics, makes it a popular choice in the electronics industry as a dielectric coating for electronic materials, and for use as anti-reflective coatings in the optical industry. Applications of CYTOP include dielectric coating for semiconductors; photo mask covers, and anti-reflective coatings. In this work, a cantilever-electret based electrostatic micro power generator with vibration in the vertical plane was set up; and the characteristic of the generated output power was examined. CYTOP was chosen as the electret material.

II. MATERIALS AND METHODS

The micro power electrostatic generator was developed by first fabricating the electret and the cantilever, and then setting up the generator.

A. Sample Electret Formation and Cantilever Fabrication

Cyclic Transparent Optical Polymer (CYTOP (CTL-809A)) from Asahi Glass Company, Japan was employed as the dielectric material. The substrate for the lower electrode was fabricated by making a sample into size of 20 mm by 20 mm from a wide copper plate with a thickness of 1.5 mm. The sample substrate was washed with ethanol and distilled water using a vibrator, after which the sample was dried using nitrogen gas. Some 2 to 3 drops of amin opropyltriethoxysilane were deposited on the copper substrate and spin-coated using a spin coater. Then, CYTOP was applied to the substrate, spin-coated and soft-baked. This process was repeated four times to obtain 8μm -thick film. After this, the CYTOP film was fully cured. Electrical connection was then made to the sample substrate to complete it as the lower electrode. The completed sample electret with a conductor connected is shown in Fig. 2.

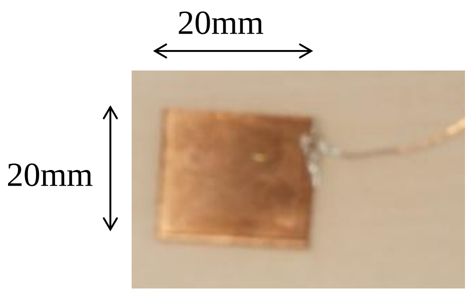

Fig 2 the completed sample electret with a conductor connected

The electret was charged using a corona discharge setup that is illustrated in Fig. 3. Charging was performed for 3 minutes after which the average surface voltage of the sample was -440V, measured at a distance of 3.8mm using an electrostatic voltmeter with a stage controller. The surface voltage of the electret was allowed to remain stable for few days before use, and diminish gradually with use. The upper electrode was made in form of a cantilever which was fabricated from a material of double-sided copper with embedded glass epoxy. T-shape cantilever was fabricated

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and is shown in Fig. 4. Electrical connection was made to the cantilever, and a thin film of laser reflector was pasted around the tip of the cantilever to aid displacement sensing of the cantilever by a laser projecting device.

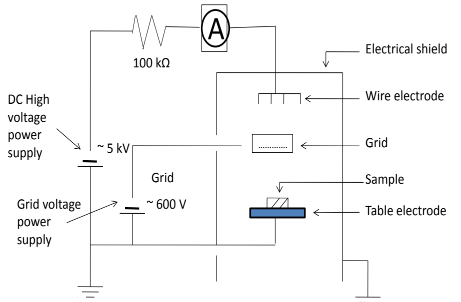

Fig 3 the corona discharge setup

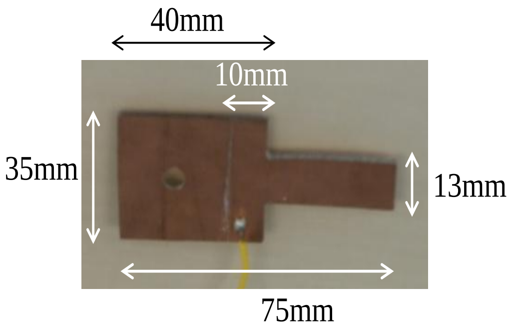

Fig 4 the fabricated T-shape cantilever with dimensions.

B. Micro Power Generation Set Up

The MEMS power generator consisted of an upper electrode (as a cantilever) and a lower electrode with electret film on it. The upper electrode was mounted on a shaker, and the lower sample substrate was attached through an insulating medium to a precision stage which is operated and controlled by a stage controller for precise movement in the vertical direction. The upper and lower electrodes were connected, through a coaxial cable, to a load resistor of 1MΩ across which the output of the generator was obtained and fed to a digital oscilloscope (Tektronix TDS2014B) for observation, measurement and data acquisition. The schematic of the developed micro-power generator set up is shown in Fig. 5.

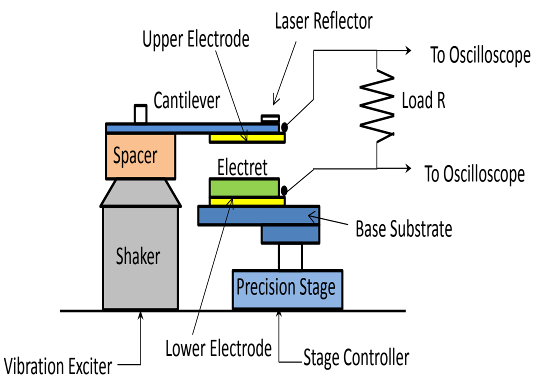

Fig 5 the schematic of the developed micro power generator set up used in the research.

C. Experimental Set up and Procedure

The schematic of the experimental set up is shown in Fig. 6. The micro power generator was mounted on a shaker and attached to the precision stage. The shaker is controlled by a laser vibrometer (ONOSOKKI LV-1710) that sets the vibration waveform, amplitude, acceleration and the frequency via a vibration exciter.

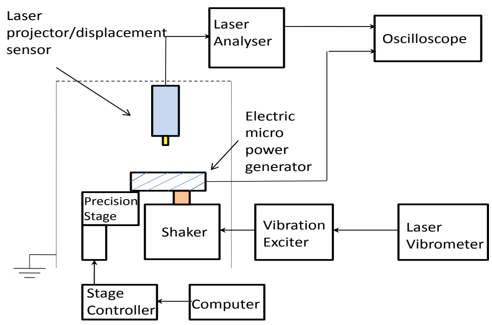

Fig 6 Experimental setup for the micro-power generation.

A laser projector/sensor was mounted close to the top of the generator to sense and measure the amplitude of vibrations of the cantilever. The laser projector/sensor works in conjunction with a Laser Impedance/Gain Phase Analyzer from which the vibration waveform was obtained via one of the input channels of the digital oscilloscope. The electrical output of the micro power generator was connected to another input channel of the digital oscilloscope. Experiment was performed on the generator by vibrating the cantilever electrode in the vertical direction using the shaker to represent mechanical vibrations from the environment. The vibration exciter was set at a frequency of 100Hz by the laser vibrometer, and the mean distance between the electrodes was varied by the precision stage. The external vibration waveform was set to be sinusoidal with preset amplitude of 0.15 mm peak-peak, and acceleration fixed at 30.2 m/s^2. The electret surface voltage was measured initially to be - 171V. Output data was acquired by the digital oscilloscope and were analyzed using MATLAB software.

III. RESULTS AND DISCUSSION

A. T-shaped Cantilever Generators' Results

Fig. 7 shows the waveforms of the input mechanical vibrations at different values of mean displacement of 0.01mm, 0.05mm, 0.15mm, 0.25mm, 0.35mm, 0.45mm, 0.55mm, 0.65mm and 0.75mmfor the T-shaped cantilever generator while Fig. 8 shows the corresponding waveforms of the generated electrical output voltage with electret surface voltage of -171V. Fig. 9 shows the frequency spectra of the waveforms of the corresponding mechanical vibrations at different values of mean displacement while Fig. 10 shows the frequency spectra of the corresponding generated electrical output voltage waveforms. The plot of average power with displacement for the T-shaped cantilever generator is shown in Fig. 11. Fig. 12 shows the plot of average power with displacement for the T-shaped cantilever generator with electret surface voltage at -110V.

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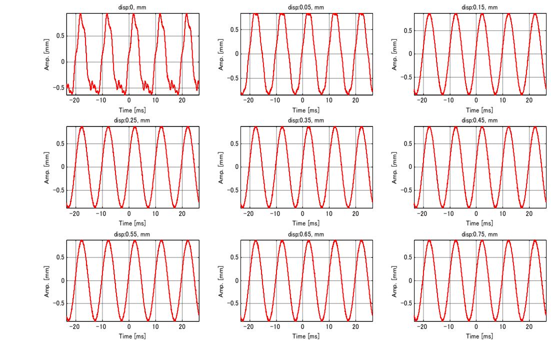

Fig 7 Waveforms of the mechanical vibrations of the T-shaped cantilever generator with varying mean displacement.

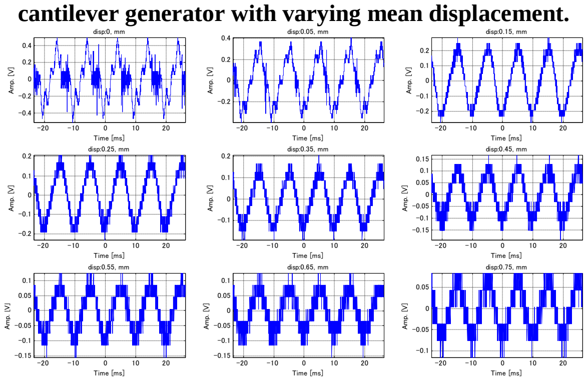

Fig 8 Waveforms of the generated electrical output voltage of the T-shaped cantilever generator with varying mean displacement. Electret surface potential is -171V, frequency of vibration is 100Hz, and the load resistance is 1MΩ.

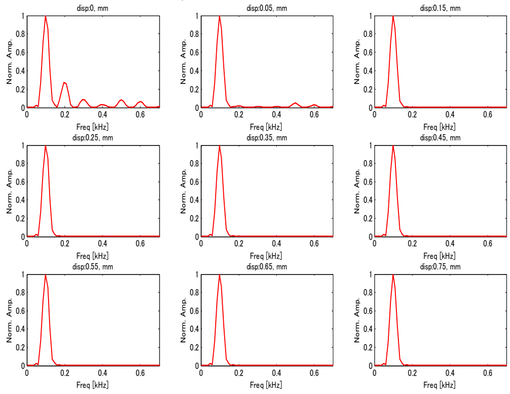

Fig 9 Frequency spectra of the waveforms of the input mechanical vibrations of the T-shaped cantilever generator.

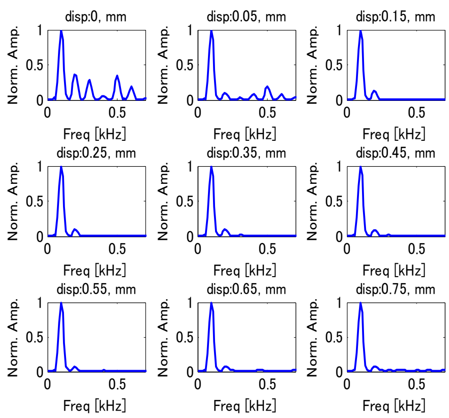

Fig 10 Frequency spectra of the waveforms of the generated output of the T-shaped cantilever generator.

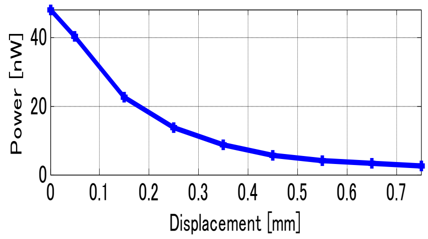

Fig 11 Plot of average power against displacement for the T-shaped cantilever generator

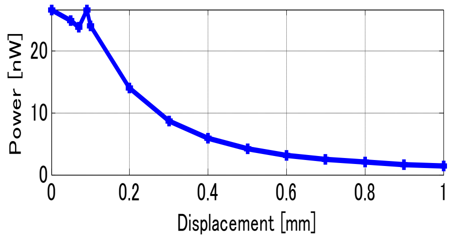

Fig 12 Plot of average power against displacement for the T-shaped cantilever generator with electret surface potential at -110V

The results of experiments conducted on the T-shaped cantilever generator in Figs. 7 to 11 showed that higher average power is generated towards the contact point between the electrodes, and it decreases exponentially as the mean displacement is increased even though the input average power is constant. However, from Fig. 8, it can be observed that the generated signals are distorted upon close proximity of the lower electrode to the upper electrode (0.01mm – 0.1mm displacement), that is, when operating in close to contact mode. This distortion was also observed from the laser output indicating the mechanical vibration waveforms of the cantilever (Fig. 7). The distortion observed in the waveforms of the mechanical vibration of the cantilevers is due to the cantilever electrode hitting the electret surface as it vibrates very close to the electret. The distortion in the electrical output is both due to distortions in the mechanical vibration and that introduced due to the extreme proximity of the cantilever to the electret surface. These distortions are also corroborated by the spectra of the waveforms in Figs. 9 and 10 which show appearance of high-amplitude frequency components higher than 100Hz for the affected cases. For dc applications involving rectification of the output signals, maximum power can be obtained in this close to contact mode of operation and the distortions will be of no consequence.

B. Ratio of Output Powers

Figure 11 shows that power output at close to contact mode is much higher than power output in non-contact mode of operation. For example, let the mean displacement for non-contact mode, y_{0nc} be 0.75 mm and the mean displacement for close to contact mode, y_{0cc} be 0.09mm (amplitude of vibration is 0.075mm (pk)). Considering ratio of average power in close to contact mode, P_{avcc} to average power in non-contact mode of operation, P_{avnc}, from Fig. 11, P_{avnc} at y_{0nc} is 1nW, and P_{avcc} at y_{0cc} is 34nW.
Therefore,

$$\left|\frac{P_{avcc}}{P_{avnc}}\right| \approx \frac{34}{1} \qquad =34.$$

The above value gives an indication that the vertical vibration based electret-cantilever micro-power generator performs maximally in close to contact mode of operation.

IV. CONCLUSION

The fabrication, set up and experimental operations of a vertical vibration based electret-cantilever micro-electric power generator was researched in this work. The cantilever was fabricated into a T-shape. Maximum output power was realized towards the contact point of both electrodes, though with distortion of generated signals. For dc applications, this is not a disadvantage. The air gap between the electret and the cantilever electrode is very important since maximum output power is realized as the air gap distance becomes smaller. The cantilever amplitude of vibration and the load resistance are also important. The maximum output power that was realized in this work with electret surface potential of -171V was about 48nW in close-to-contact mode of operation.

V. ACKNOWLEDGEMENT

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