IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 9, Issue 2 Ver. V (Mar – Apr. 2014), PP 21-27
www.iosrjournals.org

Studies on Electromechanical foam material (EFOAM) as a potential Sensor and Actuator

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Abstract: *A novel electromechanical foam (EFOAM) material capable of acting as an electromechanical transducer with integrated functions as a sensor – actuator is investigated by manufacturing some samples of the foam and performing some tests, based on the piezo–electric effect in electro-active polymers. The resulting charge, when different known weights are applied to the sample were observed and recorded with a charge amplifier while the actuator sensitivity was also estimated using the micro-scanning laser Doppler vibrometer. EFOAM is manufactured from expancel microspheres and heated by placing the microspheres in glass slides heated up to temperatures of* 135^0*C for expansion. Different samples were manufactured and charged using the corona discharge method operating under an electric field of between 11kV/cm to 15kV/cm. EFOAM displayed an electro-mechanical sensitivity of 1nm/V when characterized, and is observed that the piezoelectric nature of EFOAM exists as a characteristic of each cell within the material sample. This novel material offers much promise in the area of production of miniature electromechanical devices which maybe well applied in electroacoustic applications.*

Keywords: *Actuator, Electric charge, Electro-active polymers, Electro-mechanical foam, Piezo-electric materials*

I. Introduction

Materials exhibiting the piezoelectric effect have been discovered, observed and some proposed and in recent years, manufacturers and designers have been able to effectively apply the piezoelectric effect in these materials to various new applications. These materials include crystals, polymers, and ceramics. The piezoelectric phenomenon was first discovered in crystals by the curie brothers [1], in single crystals such as quartz tourmaline and also in lead magnesium Niobate. These materials provide various advantages such as high physical strength, low cost of manufacture, and are easy to adapt to varying requirements so as to meet various purposes.

Over the years, PZT has been the most important piezoelectric ceramic material used for actuation purposes; they consist of large piezoelectric coefficient and high dielectric constant and show a very high degree of sensitivity and high operating temperatures. These ceramics observed physically are hard, chemically inert, exhibit high stiffness, and are less affected by different atmospheric conditions. Choice of shape, size and direction of polarization can be predetermined easily [2,3]. These piezoelectric ceramics have been widely applied in manufacturing actuators, sensors and also transformers used in computer hardware. The discovery of the effect of piezoelectricity in synthetic polymers in 1960 led to the development of wide ranges of transducer devices. These synthetic polymers include polytetrafluoroethylene (PTFE), Polyvinylidene fluoride (PVDF) films and these have recently been used to develop materials which displayed a high piezoelectric characteristics and high degrees of charge retention. These classes of polymers can be easily polarized, offer low impedance resistance, are very tough and flexible and can easily be modified to different shapes for use making them highly efficient sensor actuator material [3,5].

E-FOAM is a cellular polymer which is capacitive in nature and consists of small closely packed internal voids which are electrically polarized making it suitable as an electret. Electrets are solid dielectric materials which are capable of storing large permanent electric charges[4]. EFOAM has been developed by exploring the direct and inverse piezoelectric characteristics inherent in electroactive polymers. Piezoelectricity is the ability of certain materials such as crystals, ceramics and polymers to generate an electric charge when a pressure or mechanical stress is applied while the inverse effect describes the ability of these materials to undergo a change in structure whenever an external voltage is applied[5]. This ability of EFOAM to display this piezoelectric effect offers it the possibility of functioning as both a sensor and actuator and the capability of further embedding this in a single material.

II. Materials and Methods

Materials used in the manufacture of E-FOAM include glass slides, UHU epoxy glues, insulation tapes, resistors and dry unexpanded Expancel Microspheres (031 DUX 40). Expancel microspheres are commercially available thermoplastic spheres usually occurring in milky powdered form and consist of two major constituent materials, the thermoplastic shell and a gas the blowing agent. The shell is usually a copolymer of acrylonitrile, methacrylate and acrylate and it encapsulates the blowing agent which is usually isobutene [6]. These microspheres come in different grades which are usually dry or wet and either expanded or unexpanded but for the purpose of this experiment the unexpanded grade is used.

2.1. Preparation of sample

E-FOAM samples were prepared under pressure by placing small samples of Expancel microsphere 031DUX 40 between two cleaned glass slides and held down with crocodile clips to ensure an air tight enclosure as shown in Fig.1 below.

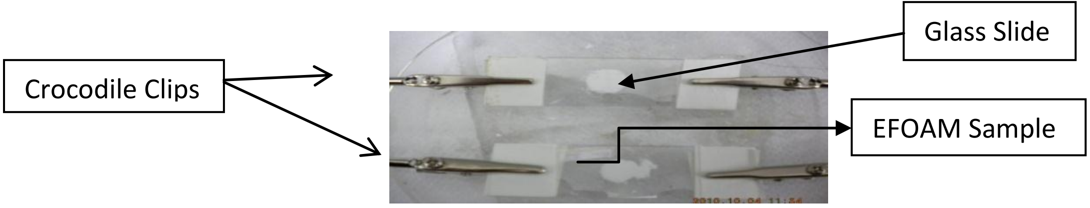

Fig.1. *Preparation of microspheres*

The spheres are placed in an oven (heraeus thermo scientific, GmbH) and the temperature manually varied between 80^{0}c to 135^{0}c for time duration of between 3 – 5mins each to obtain a well expanded foam sample. When the temperature rises above a certain range the plastic shell softens with an immediate increase in pressure due to the internal gas causing the shell to stretch and expand with increase in volume. Further application of heat leads to more expansion and removal of heat causes the plastic shell to solidify leaving the foam in this expanded state as shown in Fig.2.This method is used to produce foams of different sizes, shapes and thickness. The workable foam used during this experiment was 17mm X 15mm with a thickness of 2mm.

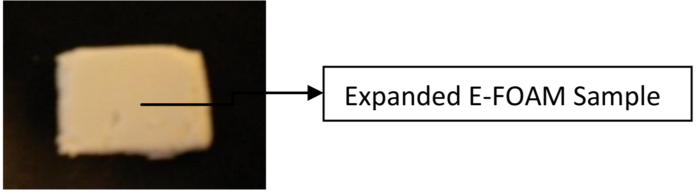

Fig.2. *Expanded sample of E-FOAM*

2.2. Charging of EFOAM sample using corona discharge method

The second step of the process involved charging the foam sample and this was done using the corona discharge method. The corona discharge method is used for non-polar materials for the injection of surface charges and space charges. The setup arrangement is as shown in Fig.3. During setup, the foam is placed on a metalized base which forms a lower electrode. The foam is held down with insulation tape as well as other parts of the base, this base is also earthed for complete circuit. The point electrode is formed using metal pins which are positioned directly above the centre of the sample at varying distances as shown in Fig.3. A circuit made up of 20 resistors each with a rating of 10MΩ giving a total of 200MΩ acts to limit the excess current in the setup preventing burn out and damage to the samples.

A conductor is attached to the pin which is directly connected to a high voltage power supply as shown in Fig.3. Constant high electric fields within the range of 11 – 20kV were applied to the sample during charging. Since this method involved the use of very high voltages, safety precautions were taken to prevent accidents. For instance after each charge, the sample was left so that the entire field discharged before lifting up the sample again. Also the charging chamber was always closed tight and blowing fan switched off.Once the charging process was complete two different methods was employed in making the charged foam a contact electrode. The first involved coating both sides of the foam with silver which acted as the electrical conductor and the second method involved applying electrical conductive metallic tapes on both sides of the foam. For both processes, thin strip wires were also connected to act as connector leads

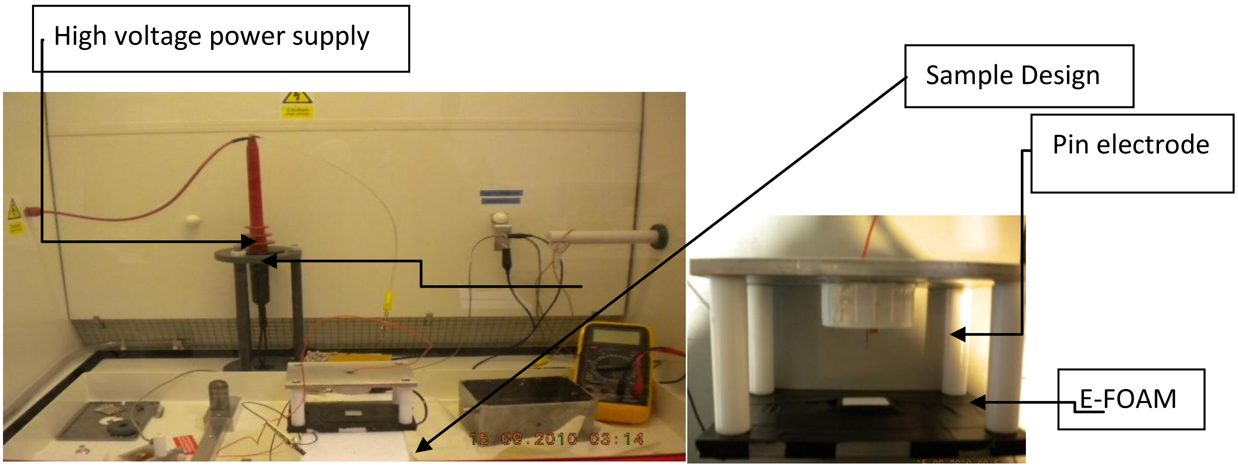

Fig.3. *Final setup for corona charging*.

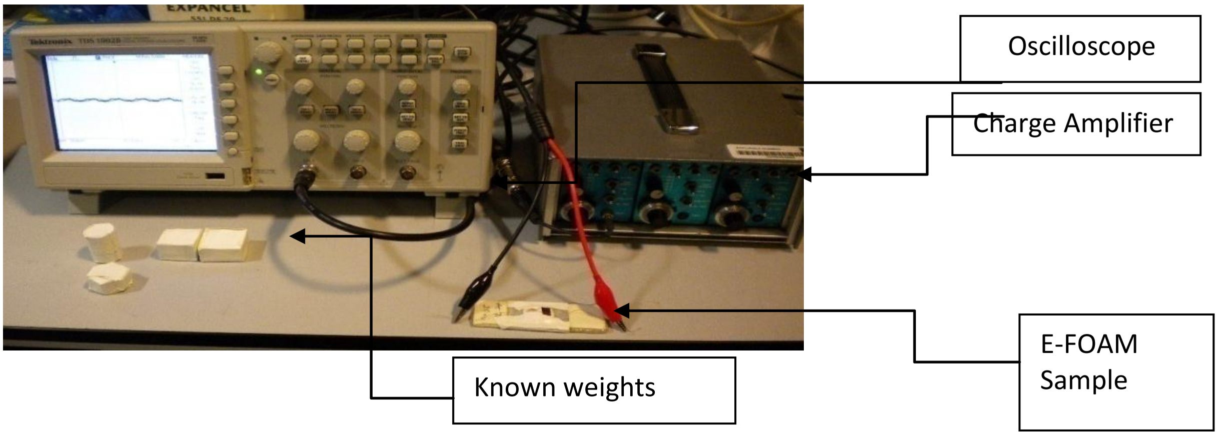

Fig.4. *Measuring direct piezoelectric properties of EFOAM*

III. Characterization

3.1 Sensor Properties

The setup for determining the sensor properties of EFOAM indicated by the direct piezoelectric effect is as shown in Fig.4. This step involved measuring the output charge of an EFOAM sample when it is compressed by application of an external force. This is achieved by applying a known force derived from metals (60g, and 90g) which are all insulated to the sample and the resulting generated charge measured using an FE – 128 – CA charge amplifier. The output voltage from the charge amplifier is readout using the oscilloscope (60MHz 1GS/s Tektronic's 1002B digital storage oscilloscope).

3.2 Actuator properties

This property relies on the inverse piezoelectric effect and it is determined in EFOAM by measuring the change in the foam thickness (displacement) when an external voltage is applied to charged foam. The response due to the change in thickness observed in the samples were measured using a laser scanning vibrometer (Polytec PSV, Berlin, Germany) as shown in Fig.5.

Fig.5. *Measuring the inverse piezoelectric effect in the EFOAM sample*

During setup, the EFOAM sample is metalized and taped firm on glass slides. These are then held in place between two metal frames in the vertical position on a tripod stand which directly faces the laser OFV – 056 scanning head. The beam from the laser doppler vibrometer is adjusted and directed at the surface of the foam to determine accurate measurements of the vibration amplitude, time and frequency due to the motion of the surface. This is usually a non-contact method. Once the target is set, different data measurements can be obtained without needing to readjust or realign the laser with the sample structure. The external voltage applied to the EFOAM sample was obtained using two different devices for test purposes. One method involved generation of the voltage using a signal generator (Agilent function generator ±10$V_{p-p,}$ 60MHz, Wokingham Berkshire UK) while another signal was generated by the vibrometers internal data acquisition board at ±3V_{p-p} and subsequently amplified using a high frequency integrated stereo amplifier (7 – 70KHz, Sony TA FE370, Sony Corporation, U.S.A). All the sample data measurements and analysis was performed by the vibrometers control unit and data management system and monitored on screen. Using fast fourier transform (FFT) as the mode of acquisition with a rectangular window and a resolution of 12.5Hz, a frequency spectrum was obtained for each signal. Signals were sampled at a sampling frequency of 51.2 KHz over an averaging count of 20 – 100. Different calculations were carried out based on excitation voltage applied to the foam an acquisition mode and the laser detection at certain frequencies to obtain desired results.

IV. Results and Discussion

The results for each part of the experiment is as outlined and discussed. The first part discusses the morphology of the manufactured EFOAM while the second part discusses the results of the charging process. Part three discusses the possibilities of EFOAM functioning as both a sensor and an actuator. It describes the estimation of the sensitivity constant d_{33} (sensor and actuation) of the EFOAM sample.

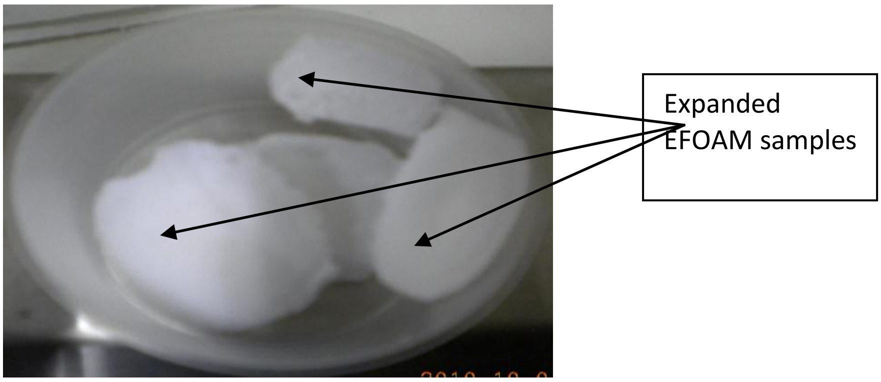

Fig.6. *Uncharged expanded EFOAM samples*

4.1 Structural Analysis

An uncharged expanded EFOAM sample is shown in Fig.6. Different samples of different sizes, shapes and thickness were manufactured. The sample has a smooth uniform surface and expands easily and optimally at a temperature of 135^{o}C although if much pressure is applied the foam might break. Since the experiment involved high temperature, safety precautions were adhered to such as using the safety gloves whenever placing or retrieving samples from the oven. The image of the internal structure of an E-FOAM sample is as shown in Fig.9 below. The image was taken using a high power stereo microscope (Leica m80). This was achieved by placing the sample on glass slides and examining both the surface of the foam as well as the broken section of the sample to get a clear image of the internal structure. The foam imaged in Fig.7 was prepared under a temperature of 135^{0}C and charged under an electric field of 15kV.

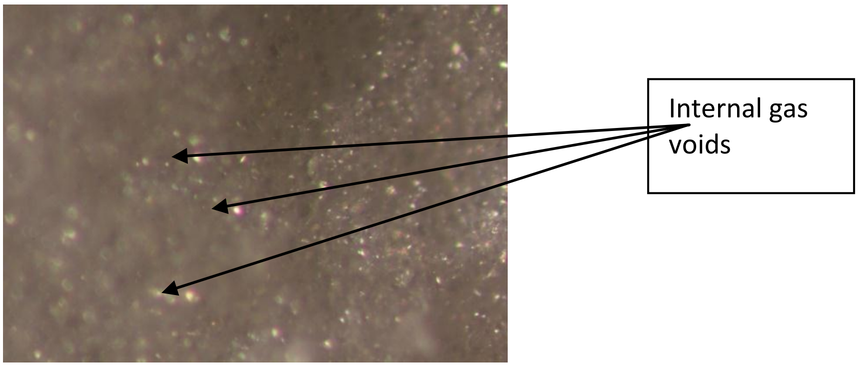

Fig.*7. Internal view of the charged EFOAM structure*

The cellular structure of the EFOAM sample is easily observed in the images above. The EFOAM sample has many gas filled voids and seems this are randomly spread within the bulk of the material. Some of the internal voids present in the foam appear more uniform, smooth and closely knitted and stacked together in some areas more than others. This high concentration of voids in EFOAM clearly endows it with higher electromechanical capabilities. The voided internal structure of EFOAM provides it with the capability of storing large permanent charges, increased flexibility as well as providing a high sensitivity constant (d_{33}). EFOAM exhibits an electromechanical sensitivity of 1nm/V. The internal charge is obtained by injection using the corona discharge method using approximately 11kVcm^{-1} – 15kVcm^{-1} fields.

4.2 Corona Charging

The aim of charging the foam using the corona method was to use an effective and readily available means to inject electric charges into the foam and verify their use as electrets. Most of the charging was carried out under high electric fields of between 11kV and 20kV although the workable charged foam was obtained under an electric field of 13kV, at this range, a uniform bluish glow was observed on the tip of the pin electrode which clearly showed the formation of electrical discharges and breakdown of the around the region of the pin and surface of foam directly underneath. It was observed that increasing the electric field above 15kV usually resulted in sharp spikes (electric arcs) which most times damaged the foam and left it uncharged. Another method which was employed was the use of multiple pins to form a sort of grid as the point electrodes (2, 4 and 6 pins), as well as varying the distance of between the pin electrodes and the centre of the foam. The multiple pin method was used to obtain a larger surface area of charged foam since using a single pin electrode only covers a smaller surface directly under the pin. Also tried was the introduction of nitrogen during the charging process although it was only observed to limit the effect of the electric field within the test chamber. Since the circuit had a total resistance of 200MΩ, applying an electric field of 13kV gives a current of 650μA through the circuit which was enough to create the required real and surface charges within the EFOAM sample. Although this method was observed to have some effects on the charging of the foam, further tests are still required for much verification.

4.3 Sensor – Actuator Properties.

The possibility of E-FOAM to function as a sensor, (direct piezoelectric effect) was observed by trying to measure the resulting charge when different known weights are applied to the sample. It was observed that the sample indeed responded by detecting the applied force but the charge output was so small to be measured using the oscilloscope. Although earlier observations indicated that applying static pressure reduces the sensitivity which could also be a reason for obtaining such result (Paajanen et al). However, windmill et al observed the foam to have a value in the range of 330pC N^{-1}. E-FOAM certainly is embedded with this property. The actuator sensitivity of EFOAM (inverse piezoelectric effect) was estimated using the micro-scanning laser Doppler vibrometer. When the foam was excited using a sinusoidal voltage across its axis of charging, the surface displacement observed was measured. The resonant frequency at which the foam produced maximum displacement was also obtained as shown in Figure 8. Different samples were investigated over the broad frequency sweep within the range 5 KHz – 20 KHz was applied. The results were obtained from the Polytec PSV 8.6 software. This is a GUI which clearly displays all the animations and responses as shown.

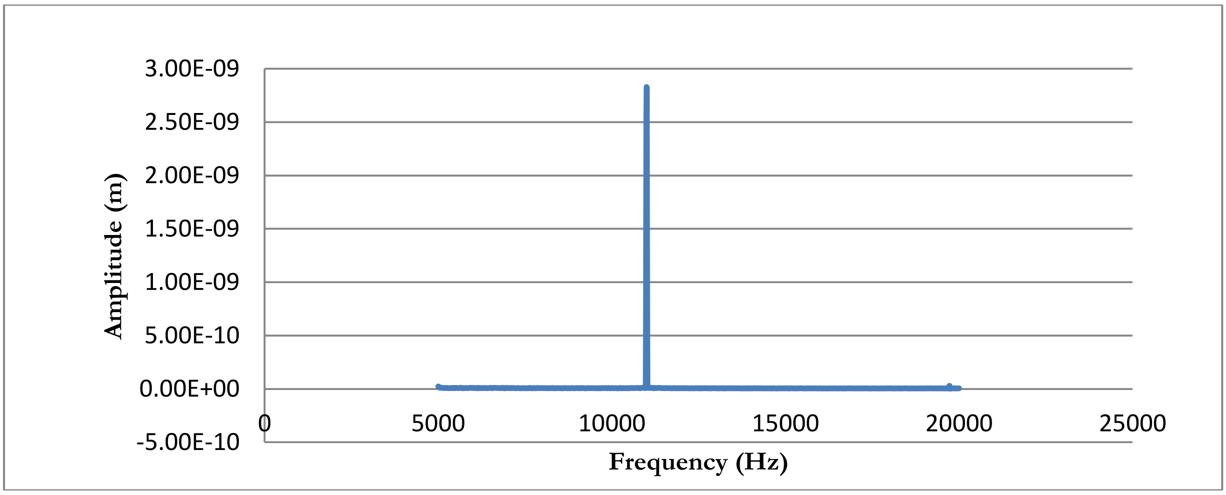

Fig.*8. Frequency and amplitude response of the EFOAM sample*

FromFig.8, it is observed that the EFOAM sample shows its resonant behaviour at a frequency of 11 KHz.Fig.9 is a graphic display of the displacement shape of an EFOAM sample. It depicts the maximum surface displacement of the sample obtained by exciting with a sinusoidal voltage of $3V_{p\text{-}p}$ at 11 kHz.Fig.10 shows the plot obtained when the sample is driven at 11 kHz for different magnitudes of displacement and voltages. It is deduced from the plots that the foam exhibits an actuation sensitivity of 1nm/V. It was also observed that although the foam showed resonant behaviour at other frequency range within 5 kHz – 20 kHz, a sharp resonant behaviour is easily obtained at 11 kHz. Comparing this with other developed cellular electrets clear shows that EFOAM produces a higher sensitivity since that obtained from EMFIT was shown to be of the order 225±25pm/V [7] and voided single – film PTFE showed 600pm/V [8] and cellular polypropylene displayed 100 – 210pm/V [9].

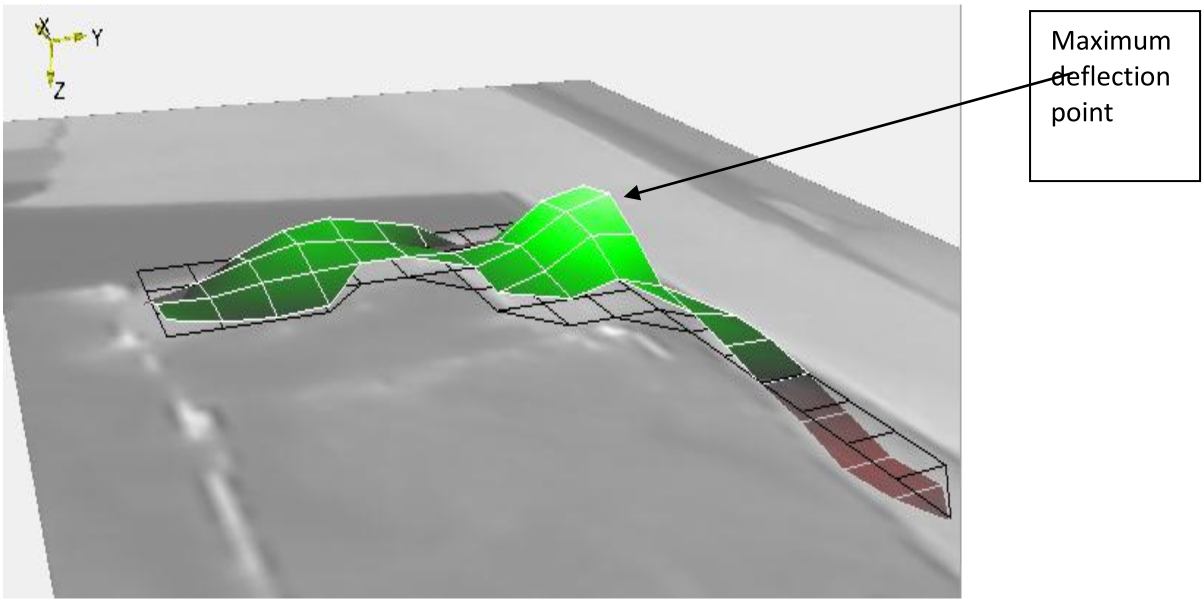

Fig.*9. EFOAM operating as an actuator.*

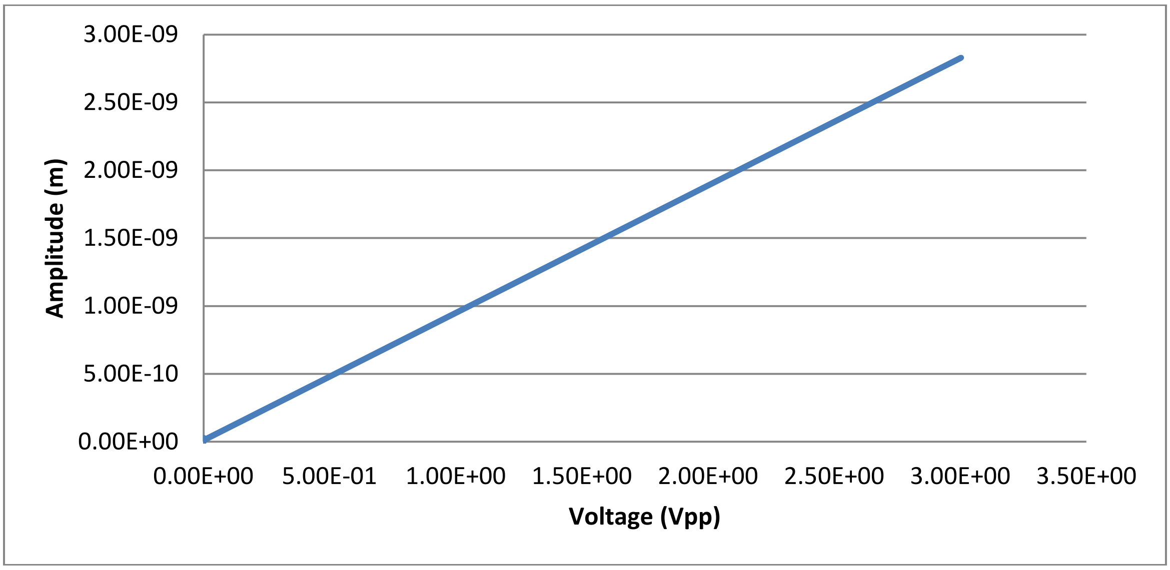

Fig.*10. Plot of voltage and displacement magnitude over 11 KHz frequency.*

V. Conclusion

The sensor and actuator characteristics of EFOAM are studied and observed using a charge amplifier and the scanning laser vibrometer. The response of the foam to generate an electric charge in response to a dynamic pressure is determined and also the response of the foam due to changes in its structure when an oscillating voltage is applied is also revealed. It is observed that the piezoelectric nature of EFOAM exists as a characteristic of each cell within the material as a result offers the promise of workability in producing miniature electromechanical devices which may be applied in electroacoustic applications. Other suggested areas of application includes the field of medicine as muscle actuators applied in biomedical prosthetics, sensor for monitoring vital signs in the body such as heart rate, blood pressures, as floor sensors in hospitals and other health care facilities to monitor patients, surveillance purposes and also can be used in active sound control and vibrations in acoustic applications such as in microphones and loudspeakers as well as in ultrasonic applications for non destructive testing [10-13]. Other areas include Aerospace applications such as in automation and control, robotics in aircrafts and space shuttles, as well as in military applications such as unmanned war vehicles and planes.

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