Finite element analysis of taper ionic polymer metal composites energy harvester

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Abstract. This paper report our recent effort on tapered in thickness IPMC in connection with the application in energy harvesting. The ability of ionic polymer metal composites to generate electrical output under mechanical deformation exploited for the development of energy harvester. In this research, new geometry (other than the conventional one) of IPMC for energy harvesting from mechanical vibrations is proposed. Uniform as well as taper in thickness IPMC cantilever beams are modelled in COMSOL for capturing the voltage and power generated by the energy harvesters. Finite element results shows that voltage across the load for taper beam is slightly greater than the uniform beam by considering same boundary, geometry and material properties.

1. Introduction

Now a day, development of new materials and their applications improved the human’s life and their life styles. Smart materials are those materials that connects the physical quantity of multiple physical domains and are described by set of state variables, such as piezoelectric materials, shape memory alloys, electroactive polymers, etc. Electro Active Polymers (EAP) are a soft and flexible class of smart materials. Ionic polymer metal composites (IPMC) considered as most promising smart material due to their large bending deformation under the low driving voltage, mechanical flexibility, lightweight and easy processing. IPMC can work in air as well as under water environment[1].

![Figure 1](image)

**Figure 1** Popular chemical structure of perfluorinated ion exchange material used as a base material for IPMC manufacturing (M+ can be replaced by other cations).

IPMC usually consists of a perfluorinated alkene with short side-chains terminated with ionic group sulfonate SO$_3^-$ (e.g. Nafion) or carboxylate COO$^-$ (e.g. Flemion) as shown in figure 1. For cation exchange and plated on both faces using noble metals such as platinum, gold, silver, copper etc., and is neutralized with counter ion such as Na$^+$, Li$^+$, K$^+$, H$^+$ etc. that balance the electrical charge of the anions covalently fixed to their backbone membrane. The large backbone gives it mechanical strength and short side chain provide ionic group that interact with water and passage for counter ion[2].

IPMC used as actuators, sensors and energy harvester. When a voltage (1-5 V) applied between two electrodes solvated mobile cations move towards the oppositely charged electrodes, resulting in swelling near the negative electrode, shrinkage near the positive electrode that leads the bending of the actuators. Conversely, the dynamic deformation of IPMC produces a stress on the backbone polymer, then an electrical potential is generated across the electrodes, due to the differential displacement of the effective centers of the anions and cations with in each cluster, producing an effective dipole leads to dynamic electric potential across electrodes as shown in Figure 2[3].
Recently, ionic polymer metal composites are gaining attention of the researchers as well as industries because of its great capabilities such as underwater application, low driving voltage, high strain, and biocompatibility so on. The potential application of IPMC are micro pumps, miniatures manipulators and grippers, robotic arm, dust wiper, micro positioning, stress sensors, pressure sensors, humidity sensors as well as great potential to harvest energy from environment in air as well as underwater such as ocean-based energy harvester[4–9].

![Figure 2 Schematic of the IPMC polymer structure and hydrated cation migration within the polymer network for mechanolectric transduction[10].](image)

Development of new low power consuming wireless sensor network, some applications require the sensor nodes to have a long lifetime. Currently these devices run on rechargeable batteries and has to replace every time to run the electronic device. Replacement of batteries is tedious and time-consuming task if these sensors, installed in remote locations[11]. Hence, acquiring the electrical power needed to operate these devices is a major concern. By trapping the thermal, light, or mechanical energies available in the ambient environment converting it into useful electrical energy to run these devices. This harvesting process helps in providing unlimited energy for the lifespan of the electronic device[12]. Therefore, the process of extracting energy from the ambient environment and converting it into useful electrical energy through suitable methods known as energy harvesting. The forms of typical ambient energies are sunlight, wind energy, mechanical energy, thermal energy, and RF energy. The devices powered by energy harvesters can be used to provide vital information on operational and structural circumstances by placing them in inaccessible locations. The classification of energy harvesting based on the form of energy available in the ambient environment they use to scavenge the power. For example, piezoelectric harvesting devices scavenge mechanical energy and convert it into usable electrical energy and stores for future use. The various sources for energy harvesting are wind energy, solar energy, thermolectric generators and mechanical vibration devices such as piezoelectric devices, electromagnetic devices[3]. Energy harvester designed by Martin is based on IPMC with a bandwidth 500 Hz with an expected power output of around 3 nW/cm² at 4 Hz operating frequency[13] and modelled the IPMC that predicts the capability of energy harvesting in air[14]. IPMC based energy harvester in different loading conditions and with different electrodes are designed and found that bending mode and platinum electrodes gives best results[15] and three dimensional disc type energy harvester for uncontrolled vibration application[16]. The underwater energy harvesting capabilities of IPMC is evaluated and power calculated across the load resistance[17] an IPMC based underwater energy harvester based upon the vibrations of a biomimetic tail, whose design inspiration is from the morphology of a thresher shark and with heterogeneous physical properties results that output is maximal when it is excited with resonance frequency and shunting resistance energy harvester matches with IPMC internal resistance [18]. The feasibility of the energy harvesting from mechanical buckling of ionic polymer metal composites induced by a steady fluid flow and analyzed through post-buckling theory of inextensible elastic beams [19]. Akle B et.al. studied a finite element fully-coupled 1D and 2D mechano-chemo-electrical model for the sensing and experimentally investigated of the effect of changing the composition of the ionomer, the membrane thickness, and electrode architecture on the sensing and energy harvesting behavior. The response of
all IPMC transducers is analyzed and compared to numerical simulations[20]. For ocean-based wave energy harvester, IPMC as suitable candidate for energy harvesting, as its response is rapid to the wave parameters such as amplitude, frequency and wavelength[21]. In this article author analyzed using FEM, the performance in starting and stable state of IPMC, the performance parameters are maximal tip deformation and voltage, its maximal stress and voltage, as well as its maximal strain and voltage and found nonlinear tendencies in the start-up state rather than linear ones[22]. Tube-shaped ionic polymer-metal composite (IPMC) mechanoelectrical transducers examined through simulation and experimental investigation for use as multi-directional sensor devices, model is independent of general geometry and can be readily applied to IPMC sensors of other complex 3D shapes[23].

IPMC is a smart material that is functionally similar to piezoelectric material, can also be used for mechanical vibrational energy harvesting purpose. For that IPMC strip is fixed from one end and mechanical force/displacement is applied at the free end, electrical output is captured through the both side’s electrode, converted this output and stored for future use using capacitor/battery.

2. Finite Element analysis of IPMC energy harvester

In this manuscript, presented a new geometry of cantilever beam as energy harvester made of IPMC. The beam shown in Figure 3 is composed of ionic conducting polymer with two pair of electrodes of platinum metal. Taper in thickness configuration of IPMC beam has been selected for energy harvesting purpose from vibrations[24].

![Figure 3 Geometry of the ionic polymer metal composite taper beam transducer.](image)

Conventionally many researchers used uniform beam for sensing, actuation as well as energy harvesting. The beam vibrated mechanically at the tip of the beam and output captured through both faced electrodes of the beam; here gray box modelling approach used for modelling the beam in FEA software for energy harvesting application. Gray box approach uses the constitutive relationship of piezoelectric material with some modification that are required for IPMC[25]. Geometrical specification of the taper as well as uniform beam selected for current analysis given in Table 1, also material properties of IPMC that are available in various literature and used for analysis given in Table 2:

| Symbol | Value | Description |
|--------|-------|-------------|
| $L_t$  | 70 mm | Total length of the beam |
| $L_f$  | 63 mm | Free length of the beam |
| $L_c$  | 7 mm  | Clamped length of beam |
| $w$    | 8.60 mm | Out of plane dimension of beam |
| $t_0$  | 0.2 mm | Fixed end thickness of taper beam |
| $t_1$  | 0.5 mm | Free end thickness of taper beam |
| $t$    | 0.2 mm | Thickness of uniform beam |
Table 2 Equivalent material properties of IPMC.

| IPMC Parameters     | Symbol | Value      | Reference            |
|---------------------|--------|------------|----------------------|
| Density             | \( \rho \) | 3385 kg/m\(^3\) | Zhang L 2007[26]     |
| Young’s Modulus     | \( Y \)  | 1.158 GPa  | Nemat Nasser 2000[27]|
| Poisson’s Ratio     | \( \nu \) | 0.487      |                      |
| Dielectric Constant | \( \epsilon \) | 3.8e\(^{-5}\) F/m | Barramba 2007[28]   |
|                     | \( d_{31} \) | 1.750e\(^{-7}\) C/N | Peng 2010[22]       |
|                     | \( d_{32} \) | 1.750e\(^{-7}\) C/N | Zhang L 2007[26]    |
| Piezoelectric constants | \( d_{33} \) | 0           |                      |
|                     | \( d_{15} \) | 0           |                      |

Ionic polymer metal composite beam can be modelled as a bimorph piezoelectric beam with polarized in opposite direction as shown in Figure 4 that captures the movement of ions present inside of the IPMC. Bimorph modelling of uniform as well as taper beam equivalent to the IPMC is shown in Figure 5, left side is for uniform beam and right side shows the taper beam used for modelling in COMSOL. Voltage, power and tip deflection, are major parameters of IPMC energy harvester that has been examined using COMSOL Multiphysics for uniform as well as taper beam[29].

IPMC beam modelled as 2-Dimensional geometry (listed in table 1) in COMSOL, piezoelectric devices module utilized for finite element simulation of energy harvester in COMSOL. For simplifying the finite element analysis of IPMC without reducing the calculation accuracy, the ingredients of the IPMC material can be assumed to be uniform, the dielectric constant along the x direction and y direction are the same, and the deformation is elastic. In this case, the IPMC material parameters (listed in table 2) have been substituted for those parameters equivalents in PZT ceramics due to the electromechanically coupling analogy technique of the COMSOL, designed for piezoelectric materials (such as PZT ceramics). Furthermore, it is suitable to assume both \( d_{33} \) and \( d_{15} \) equal to zero because only the \( d_{31} \) and \( d_{32} \) modulus utilized in this finite element analysis method.
Displacement applied at the free end of the IPMC beam and fixed at another end are the mechanical boundary conditions necessary for the analysis of taper and uniform beam while Electrical boundary condition are output captured both the faces of the IPMC beam. Taper and uniform beams meshed with quadrilateral element with mapped meshing with distribution along length and thickness of the beam as shown for uniform beam Figure 6 and for taper beam Figure 7 and their exaggerated view.
3. Results and Discussions

In this paper, taper IPMC geometry as the energy harvester in cantilever configuration is presented. Conventional geometry i.e., uniform in thickness, beams used by many researchers in cantilever beam configuration, so taper IPMC beam harvester and uniform beam energy harvester compared for maximum power output from mechanical vibration. The optimal parameters for maximum power output from energy harvester calculated by first finding the frequency at which dissipated voltage across load resistance with the help of frequency response analysis of uniform as well as taper beam by setting random value to load resistance as shown below in Figure 8.

Then after finding the frequency at which voltage is maximum, power dissipated across the load resistance is calculated by setting the random value of load resistance and exciting the harvester with different frequencies as shown in Figure 9 for uniform as well as taper beam energy harvester.

Figure 7 Meshing of the IPMC taper beam for finite element simulations of energy harvester.

Figure 8 Frequency response results of IPMC beam for voltage across the load resistance under different exciting frequency for Uniform beam peak at 22.1 Hz and for taper beam, peak at 5 Hz.
Figure 9 Frequency response results of IPMC beam for power across the load resistance under different exciting frequency for Uniform beam peak at 22.1 Hz and for taper beam, peak at 5 Hz.

Frequency at which the power output is maximum is selected as the excitation frequency i.e. for uniform beam the exciting frequency is 22.1 Hz and 5 Hz for taper cantilever beam. Next step was finding load resistance at which power dissipated is maximum. Voltage across the load calculated by varying the load resistance from 1 to 100 Ω at the fixed exciting frequency of 22.1 Hz and 5 Hz respectively. Hence optimal load resistance for maximum voltage across the load for uniform beam found as 39.81 Ω for uniform and 3.981 kΩ for taper beam energy harvester as shown in Figure 10.

Figure 10 Voltage dissipated across the varying load resistance under fixed excitation frequency of 5 Hz for uniform beam and 22.1 Hz for taper cantilever beam energy harvester.

The load resistance at which the power dissipated across the load resistance found out by varying the load resistance and exciting the harvester with fixed excitation frequency 22.1 Hz for uniform beam and 5 Hz for taper beam for maximum power dissipation. Dissipated power is maximum at 10 Ω for uniform beam and maximum at 15.849 Ω for taper beam as shown in Figure 11.
Figure 11 Power dissipated across the varying load resistance under fixed excitation frequency of 5 Hz for uniform beam and 22.1 Hz for taper cantilever beam energy harvester.

Therefore, optimum parameter for maximum power output from uniform beam is 22.1 Hz frequency and 10 \( \Omega \) resistance harvests voltage of 0.038 V and maximum power dissipated is \( 3.26 \times 10^{-4} \) watt. Similarly, for taper cantilever beam 5 Hz frequency and 15.849 \( \Omega \) resistance, harvests the voltage of 0.0412 V and power dissipated is \( 8.25 \times 10^{-5} \) watt.

4. Conclusions
In this paper, finite element analysis of taper as well as uniform IPMC beam performed for the application of energy harvesting from vibration. Gray box modelling approach used to simulate the energy harvester. Geometrical as well as material properties selected from previous literatures of energy harvesting using IPMC. From FEM results, it can be concluded that for the same geometric as well as material properties voltage output across the load resistance for taper beam is slightly greater than the uniform beam. In addition, the power dissipated across the load for uniform beam is greater than the taper beam. This is because of higher internal impedance of taper beam. Hence, taper beam can be used for enhancing the energy harvested from vibrations. In this paper only one taper section is selected for FEA simulation, in future energy harvested can be further enhanced by optimizing the taper ratio of IPMC for energy harvesting.

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