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ORIGINAL ARTICLE

Effects of Varied Planar Dimensions of IPMC on Simulated Actuation using COMSOL

Danial Haziq Rizal[1], Wan Hasbullah Mohd Isa[1,*], Muhammad Amirul Abdullah[1], Anwar P. P. Abdul Majeed[2] and Norasmiza Mohd[1]

[1]Faculty of Manufacturing & Mechatronic Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600, Pekan, Pahang, Malaysia.
[2]School of Robotics, Xi'an Jiaotong-Liverpool University, Taicang, Suzhou, 215400, China.

ABSTRACT – This study focuses on mechatronic systems and their use of bending smart materials, specifically the ionic polymer metal composite (IPMC), for compliant actuation. The advantages of IPMC actuators, such as low power consumption and high flexibility, are highlighted. The actuation mechanism of IPMCs involving ion migration, water transport, and mechanical stress imbalance is discussed. The influence of geometric parameters, specifically length and width, on IPMC performance is investigated through simulations. Results show a positive correlation between IPMC lengths exceeding 30 mm and displacement, with longer lengths leading to higher displacements. The relationship between width and maximum displacement is attributed to factors like increased active area, larger polymer volume, and potential effects on mechanical properties. Further electromechanical analysis is needed for a comprehensive understanding of these mechanisms.

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INTRODUCTION

Mechatronic systems are a combination of mechanical components, electrical components, and computer systems. They are used in a wide variety of applications, including compliant locomotion systems [1], small-scaled robotics [2], energy harvesting [3][4] (even though not as effective as electromagnetic harvesters [5][6]), biomedical instrumentation [7] and robotics [8].

One of the key challenges in mechatronic system design is achieving the desired level of compliant actuatio i.e. the ability of a system to deform 'softly'in response to stimulus input. One common approach is to use bending smart materials. Bending smart materials are materials that can change shape in response to an electric field [9]. One example of a bending smart material is the ionic polymer metal composite (IPMC), which is made of a polymer film that is coated with metal electrodes [10]. When an electric field is applied, the ions in the polymer film move, which causes the film to bend [11].

IPMCs have a number of advantages for use in mechatronic systems. They are low-power, which makes them ideal for battery-operated applications. They are also fast, which makes them well-suited for dynamic applications. In addition, IPMCs are very flexible, which allows them to be used in a wide variety of applications. The use of IPMC actuators is an emerging trend in mechatronics. These actuators offer a number of advantages over traditional actuators, such as low power consumption, scalability, easiness to shape and integrate, as well as high flexibility [12].

IPMC actuation involves ion migration, water transport, and mechanical stress imbalance. When a voltage is applied, positively and negatively charged ions migrate within the ion-exchange polymer, driven by the electric field. Simultaneously, the electric field influences water movement through electro-osmotic drag. This leads to an asymmetrical distribution of water, causing regions of swelling and shrinkage. The resulting mechanical stress imbalance causes bending or deformation [13], as illustrated in Figure 1.

It is crucial to note that the specific behavior of IPMC actuation can vary depending on factors such as the composition of the ion-exchange polymer, electrode materials, environmental conditions, and actuator geometry [14]. In term of geometry, IPMC length determines range of motion and deflection. Longer actuators offer broader range but may have limitations in force and response time. Width affects stiffness and deflection. Wider actuators have higher stiffness, while narrower ones provide flexibility. Height influences thickness and mass distribution. Thinner actuators are more flexible but may compromise strength.

This paper aims to study the effects of different planar geometric parameters i.e. length and width on the performance of IPMC actuators. Through simulation, it seeks to gain insights into how variations in these parameters influence crucial actuation characteristics. The findings will contribute to the design of tailored IPMC actuators that meet specific application requirements in mechatronic systems.

***CORRESPONDING AUTHOR** | Wan Hasbullah Mohd Isa | ✉ wanhasbullah@umpsa.edu.my

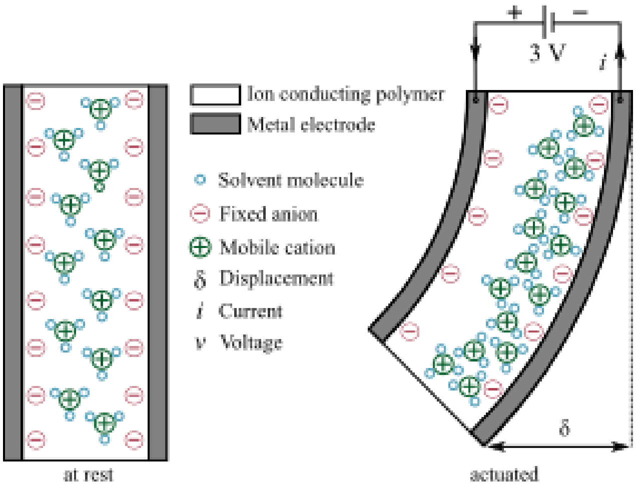

Figure 1. Ion migration during the actuation of IPMC, consequently generating bending deformation.

This paper comprises four sections: Related Works, Methodology, Results and Discussion, and Conclusion. The Related Works section reviews prior research on IPMC actuators and their geometric parameters. The Methodology section describes the simulation and analysis techniques used. The Results and Discussion section presents the findings, analyzing the impact of geometric variations. The Conclusion summarizes the key findings and proposes future research directions.

RELATED WORK

This section provides an overview and synthesis of relevant works investigating the variation of dimensions of Ionic Polymer-Metal Composites (IPMCs) and their influence on tip displacement.

He et al (2011) study the influence of Nafion membrane thickness on the performance of IPMCs. By varying the membrane thickness (0.22 mm, 0.32 mm, 0.42 mm, 0.64 mm, and 0.8 mm), the elastic modulus and blocking force of the IPMCs are found to increase, while the current and displacement decrease. The IPMC with a thickness of 0.8 mm exhibits the highest blocking force. An electromechanical model supports these results, but without considering water electrolysis, the simulated outcomes slightly exceed the experimental data [15].

Li (2011) examines thick IPMC fabrication using the hot-pressing method and investigates the impact of thickness on tip forces and water uptake capability. The study also explores the relationship between IPMC length and tip forces using 2-film samples of uniform width (6 mm) and lengths (15 mm, 30 mm, and 45 mm). Experimental results demonstrate that increasing IPMC thickness reduces water uptake capability while increasing maximum tip force under 4.5V DC voltage. Additionally, elongating IPMC length decreases maximum tip forces observed [16].

Sun et al (2015) conducted experiments to assess the performance of IPMC actuators, measuring their mechanical and electrical properties. The IPMC samples had dimensions of 40mm x 10mm x 0.3mm and a weight of 0.2g. Our findings showed that the maximum displacement was directly proportional to the applied voltage until saturation. The tip displacement increased with the strip's effective length, while external loading had minimal impact. The blocked force exhibited a nonlinear relationship with the effective length [17].

Pugal et al (2016) offers a detailed guide for modeling electromechanical actuation of IPMC materials using COMSOL Multiphysics software, which is the foundation of this work. They explain the physical functions of IPMC actuation phenomena and investigates the electromechanical and mechanoelectrical transduction phenomena of these materials [18].

Li and Yip (2019) investigate the influence of thickness and length on the performance of IPMCs. Their findings show that increasing the thickness enhances the maximum tip force but prolongs the response time, while reducing the length achieves a double-maximum tip force without extending the response time [19].

Zhang et al (2021) systematically analyzes the structural characteristics of IPMC and evaluates the effects of varying sample lengths (ranging from 1 to 5 cm with a width of 0.5 cm) on electrical parameters and actuation behavior. The study concludes that the electrical parameters of IPMC materials, such as capacitance, electrode resistance in the thickness-direction, and internal resistance, decrease as the sample length increases, while the bending strain of the setpoint increases [20].

In term of sensing, MohdIsa et al (2019) provides a comprehensive review of research on utilizing IPMCs as deformation sensors. The focus is on investigating the modeling of IPMC sensing phenomena and exploring the implementation and characteristics of various sensing methods. The proposed methods are categorized into active sensing, passive sensing, and self-sensing actuation techniques. [21] They also investigates and compares the frequency responses and noise dynamics of various active sensing signals in IPMCs, namely voltage, charge, and current [12][22].

METHODOLOGY

This chapter describes the methodologies employed to achieve the objectives and goals of the project. It encompasses details regarding the software utilized, the selected physics model, the defined parameters, and the simulation procedures.

COMSOL Multiphysics version 5.6 is utilized in this study for pair analysis and modeling purposes due to its interactive and user-friendly nature for simulations. The software incorporates mathematical equations, enhancing its usability for a wide range of users. The primary aim of this simulation is to examine the influence of IPMC dimensions on the resulting displacement.

The simulation was carried out iteratively, considering various dimensions of IPMCs to examine their influence on displacement. In the first research parameter, IPMCs with different lengths (10 mm, 20 mm, 30 mm, 40 mm, and 50 mm) were designed, while maintaining consistent thickness and width. The second research parameter involved altering the width of the IPMCs while keeping a fixed overall length of 30 mm. Widths of 5 mm, 10 mm, 15 mm, and 20 mm were employed for this analysis. The excitation frequency is fixed at 1 Hz for all simulations. All other parameters are the same as in [18].

In conclusion, this chapter presented the methodologies employed for achieving the project objectives. The simulations involved investigating the influence of IPMC dimensions on displacement through iterative examination of different IPMC lengths and varying widths.

RESULTS AND DISCUSSION

Figure 1 illustrate an output of the simulation of IPMC actuator using COMSOL. We investigate the displacement amplitude of the excited frequency that are generated during the actuation.

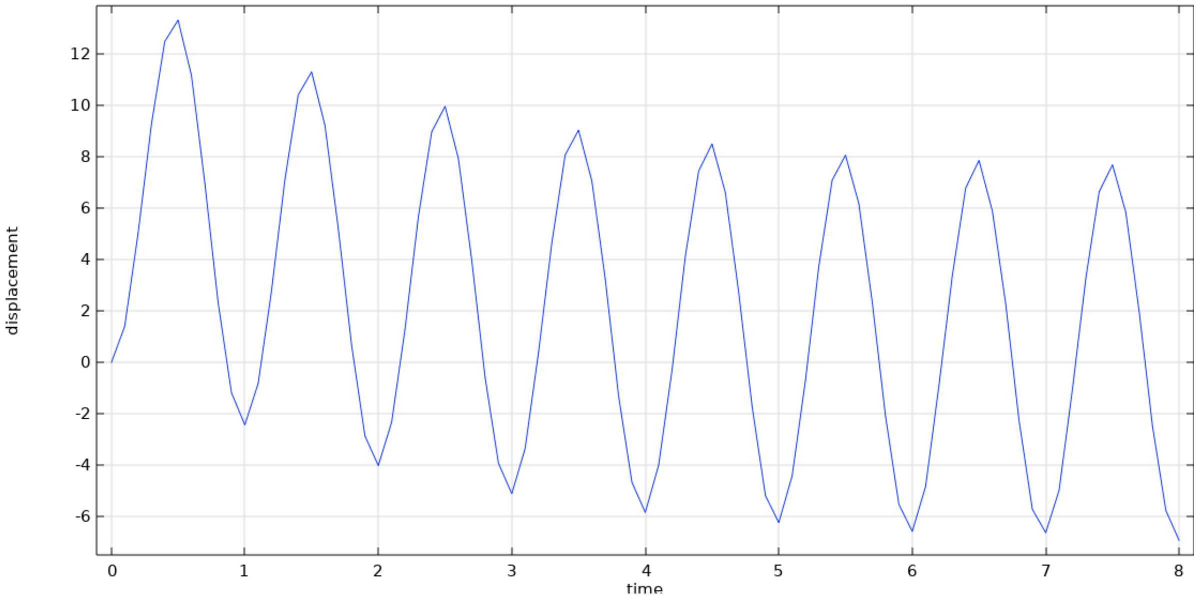

Figure 2. Simulation output of IPMC actuator using COMSOL (40 x 10 x 0.60 mm).

The first investigation focused on maintaining a constant depth of 10 mm, polymer thickness of 0.57 mm, and electrode thickness of 0.01 mm while exploring the effects of five distinct IPMC lengths, namely 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm. Figure 3 demonstrates a positive correlation between IPMC lengths exceeding 30 mm and displacement, highlighting an increasing trend wherein longer lengths coincide with higher displacements.

The maximum displacements for different lengths of the IPMC were shown in Figure 3: 10 mm length had a maximum displacement of 0.02 mm, 20 mm had 0.11 mm, 30 mm had 0.8 mm, 40 mm had 7.2 mm, and 50 mm had 13.3 mm. The results suggest a positive correlation between the length of IPMC specimens and their maximum displacements. As the length increased from 30 mm to 50 mm, a rapid increase in maximum displacement was observed. This relationship can be attributed to factors such as the larger active area for charge distribution, increased volume of ionic polymer material, and potential influence on mechanical properties.

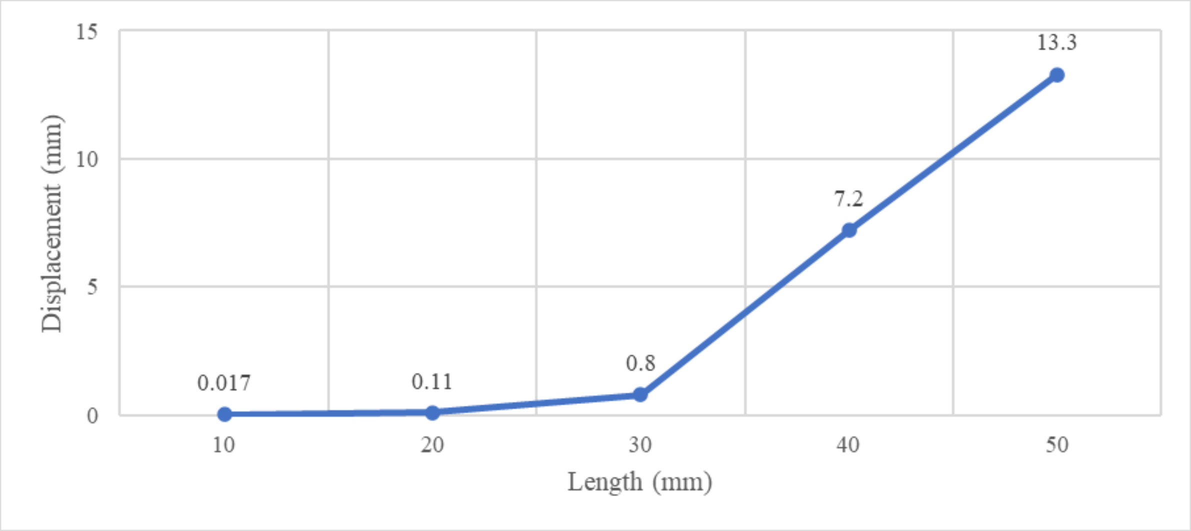

Figure 3. Tip displacement of IPMC with varied lengths.

The second study focused on maintaining a constant IPMC length of 30 mm, polymer thickness of 0.57 mm, and electrode thickness of 0.01 mm, while varying the depth across four levels: 5 mm, 10 mm, 15 mm, and 20 mm. Figure 4 displays the simulated maximum displacements of IPMC with varying widths: 0.43 mm, 0.85 mm, 1.3 mm, and 1.7 m. The observed correlation between width and maximum displacement can be ascribed to interconnection of factors such as an increased active area facilitating charge distribution, a larger volume of ionic polymer material enhancing actuation capabilities, and a potential influence on mechanical properties. Nonetheless, further in-depth electromechanical analysis is essential to fully comprehend the underlying mechanisms driving this relationship.

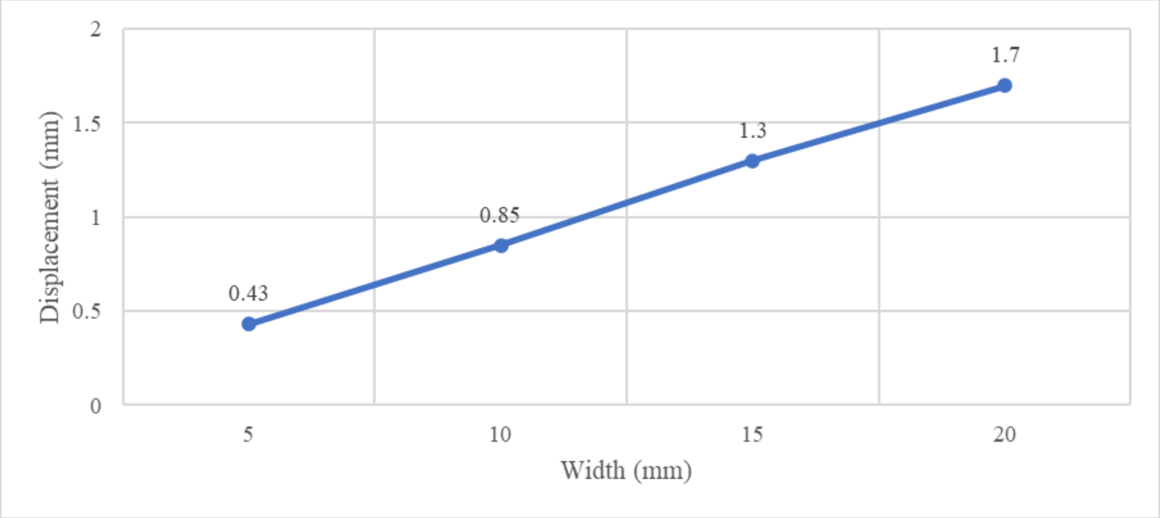

Figure 4. Tip displacement of IPMC with varied widths.

CONCLUSION

Achieving compliant actuation for a mechatronic system is a challenge. IPMCs are commonly used as bending smart materials with advantages like low power consumption, fast response, and flexibility. IPMC actuation involves ion migration, water transport, and stress imbalance, causing bending. Length and width impact motion range, stiffness, and flexibility. This study examines their effects on IPMC actuator performance for tailored designs using COMSOL simulation.

IPMC lengths over 30 mm positively correlate with displacement. Increasing length from 30 mm to 50 mm significantly increases displacement due to larger charge distribution area and increased polymer volume. The observed correlation between IPMC width and generated displacement is attributed to factors like increased active area, larger polymer volume, and potential effects on mechanical properties. Further analysis is required to understand these mechanisms fully.

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