On the optimal design of an Ionomeric Polymer Metal Composite (IPMC) actuator

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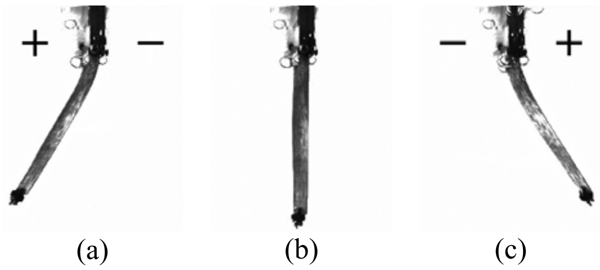
Abstract

This paper investigates design considerations of an Ionomeric Polymer Metal Composite (IPMC) actuator in a cantilever beam configuration. We investigate a general case where the actuator is required to apply certain output force within a predefined working section. We show how to find the optimal width and length of the actuator given these constraints. Our approach also considers an actuator configuration where part of the IPMC actuator is replaced with a rigid elongation. One of the conclusions of this work is that the rigid elongation can be used as a construction element to improve the performance of the IPMC actuator.

Subject classification numbers
81.05.Lg (Polymers and plastics; rubber; synthetic and natural fibers; organometallic and organic materials)
82.35.-x (Polymers: properties; reactions; polymerization)
82.35.Lr (Physical properties of polymers)

1 Introduction

IPMC (Ionomeric polymer metal composite) is a type of an electroactive material that bends in electric field [1, 2]. It consists of a thin swollen polymer film, such as Nafion^{TM}, filled with water or ionic liquid. Both sides of the polymer film are plated with thin metal electrodes. Voltage applied between the surface electrodes causes migration of ions inside the structure of the polymer, which in turn causes the mechanical bending of the sheet as shown in figure 1. The direction of bending depends on the polarity of the applied electric field.



(a) (b) (c)

Figure 1. IPMC with (a and c) and without (b) electrical stimulation.

This paper investigates the optimal design of the IPMC actuator in a cantilever beam configuration. It is based on a mechanical model developed in our previous work [3].

Compared to other mechanical and electromechanical models developed so far [4, 5, 6, 7, 8, 9, 10] our model is more general in the sense that it permits modeling large deflections at non-uniform bending. Moreover, it also permits considering the case where part of the IPMC sheet is replaced with a rigid elongation and when an external force is applied to the beam. We have previously demonstrated experimentally that the model is in a good correlation with the experimental data [3].

The developed general mechanical model permits studying the properties and design considerations of the IPMC actuator in a general case, where the actuator can move with large deflections and where external force is applied to the actuator. It also permits comparing the performance of the IPMC actuator with and without a rigid elongation.

In this paper we show how the task requirements affect the optimal design of the IPMC actuator. We demonstrate how the requirements to the actuation length of the actuator and to the output force determine the optimal design. Furthermore, we demonstrate that the actuators with and without a rigid elongation have a different performance in case of different task requirements and that the actuator with a rigid elongation can be superior to the actuator without an elongation. We then continue showing what is the optimal length and width of the IPMC sheet with a rigid elongation when the actuator is optimized by the mechanical work per unit area of the IPMC sheet.

Previously, the use of elongation has been studied in [11] but the model developed there is only accurate in case of small deflections. In [12, 13] the properties of IPMC actuators are studied but optimal design is not considered. Optimal length of the actuator is discussed in [14], but in different context (IPMC sheet rests on human tissue and optimal electrode length for maximum deflection and pressure is found).

2 The model

This section briefly describes the mechanical model developed in [3] that is used to find the optimal configuration of the actuator.

Our objective is to model a situation, where an IPMC sheet in a cantilever configuration applies force to an object (load cell, for example). The sheet can have an absolutely rigid elongation attached to the tip. In this study we model the sheet in a static equilibrium state (the sheet does not move).

The shape of an IPMC sheet is modeled as a curve in 2D space (see figure 2). The curve is a projection of the neutral surface of the sheet – the surface that does neither contract nor expand. Throughout this paper s denotes the natural parameter of the curve that specifies a position on the sheet at distance s from contacts along the curve.

The object is located on a circular trajectory in position p (see figure 2) where p specifies a position on the trajectory at distance p from zero position along the trajectory. The center of the circle is at the contacts of the sheet and the radius is denoted as R. The force applied to the object in direction of the tangent of the trajectory is denoted with $F(p)$ (also called output force of the actuator). In [3] force is written without parameter but here we emphasize the dependency form position. Usually we are only interested in $F(p)$ for a specified section $[p_1, p_2]$ of the trajectory called the working section.

A part of the IPMC sheet is fixed between contacts at clamps or the elongation. This part does not influence the sheet behaviour. The freely bending IPMC part of the sheet is characterized by the following parameters

1. length - l,
2. initial curvature - $k_0(s)$,
3. beam stiffness - D,

4. electrically induced bending moment (shortly EIBM) - $M_{\mathrm{e}}(s)$.

Parameters $k_0(s)$ and $M_{\mathrm{e}}(s)$ are only defined for positions $s \in [0, l]$. For the elongation they are undefined. If we assume, that $M_{\mathrm{e}}(s)$ does not vary along the sheet, the notation M_{e} may be used instead. EIBM depends obviously on electrical stimulation. In this paper we are going to investigate different electrical stimulations in parallel. A superscript is added to the notations of output force $F(p)$ and EIBM $M_{\mathrm{e}}(s)$ or M_{e} to distinguish them.

The same model can be used for modeling both the actuators with and without elongation. Formally every IPMC sheet is considered to have an elongation (see figure 2). It helps to model elongated sheets but can equally be used for modeling sheets without an elongation. Elongation starts from a position l. It is absolutely rigid and straight.

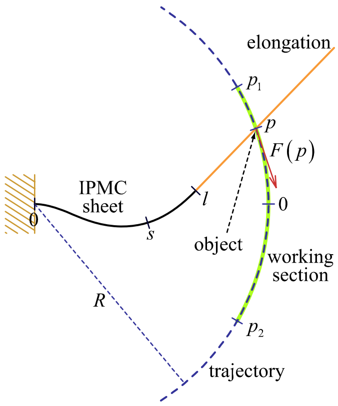


Figure 2. Actuator.

Output force F, beam stiffness D and EIBM $M_{\mathrm{e}}(s)$ are proportional with the width w of the sheet. For example, if we double the width of the IPMC sheet, it is equivalent to two sheets working in parallel and output force, beam stiffness and EIBM would double. Parameters D and $M_{\mathrm{e}}(s)$ normalized to the width of the sheet characterize the properties of the IPMC material.

3 Previous work

The model described above is described in more detail and validated in [3] together with details about parameter extraction, experimental system setup and discussion of the results. Since our model also permits modeling an IPMC actuator with a rigid elongation we have conducted comparative experiments to verify the model in both cases. Moreover, we have also verified models with a constant and changing EIBM.

The experimental results show that the model is well coherent with the experimental data. The model with the varying EIBM is much better in accordance with the experimental data than the model with a constant EIBM. This indicates that the EIBM changes along the length of the actuator, been largest at the contacts where voltage is applied and decreasing towards the tip. This is the main reason of the non-uniform bending of the actuator and our model permits describing this non-uniform behavior accurately.

The experimental results also show that the position-force relationship of a short IPMC actuator with an elongation is linear while the position-force relationship of an IPMC actuator without an elongation and of the equal length is non-linear. This result is significant from the point of view of the actuator control.

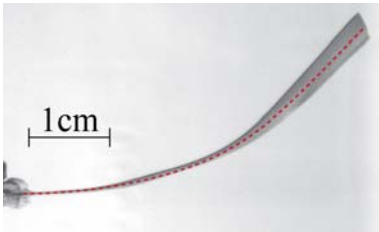
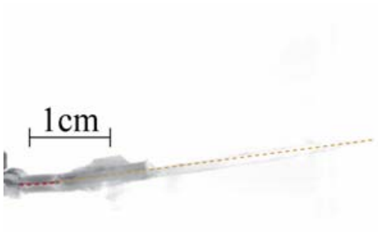
The current paper uses the described model to study the optimal design of the IPMC actuator. We use the parameters extracted in [3] to extend and compare the results of our previous work.

Similarly to the previously conducted experiments, our objective is to investigate how the rigid elongation changes the performance of the actuator and whether it can be used as a construction element to make the actuator more efficient.

4 Parameters of the actuators

In this section the properties of the two actuators (with and without elongation) are presented. For details about parameter extraction, experimental system setup and discussion of the results please refer to [3]. Table 1 summarises information about the dimensions of actuators.

Table 1. Dimensions of the actuators.

Configuration	Long IPMC sheet	Short IPMC sheet with the plastic elongation
Side view of the sheet and the initial neutral curve (the red line) with curvature - $k_0(s)$.		
Length of the freely bending IPMC part - l	50 mm	4.5 mm
Length of the part of the IPMC sheet that is fixed - l_c	1.5 mm	3.5 mm
Width of the IPMC sheet - w	11 mm	11 mm
Thickness of the IPMC sheet - d	0.21 mm	0.21 mm

Parameter l_c specifies the length of the IPMC sheet that is fixed between contacts at clamps or elongation. This parameter does not influence the behavior of the sheet but we do use it later on to calculate energy per area of IPMC sheet. Parameters w and d , on the other hand, have a direct impact to the sheet's behavior. They are not explicitly used in the model but model parameters D and $M_e(s)$ are related to them. They are measured to assess the parameters of the IPMC material.

Throughout this paper we call actuators corresponding to sheets introduced "long sheet" and "short sheet" respectively. The radius of the trajectory is $R = 0.04\,\text{m}$.

For both of the sheets, EIBM-s at +2V and at −2V are considered. Table 2 summarizes the notations for EIBM-s. We let EIBM vary along the sheet and also consider an assumption that it is constant.

Table 2. Notations for EIBM.

Electrical stimulation	Possibly varying EIBM	Constant EIBM
+2V	$M_e^+(s)$	M_e^+
−2V	$M_e^-(s)$	M_e^-

Beam stiffness and constant EIBM are presented in table 3. Varying EIBM is presented in [3].

Table 3. Beam stiffness and EIBM.

Configuration	Notation (equation)	Long IPMC sheet	Short IPMC sheet
Beam stiffness	D	$2.03\cdot10^{-6}\ \mathrm{N\cdot m^2}$	$1.21\cdot10^{-6}\ \mathrm{N\cdot m^2}$
Beam stiffness normalized to the width of the sheet	$\frac{D}{w}$	$1.84\cdot10^{-4}\ \mathrm{N\cdot m}$	$1.10\cdot10^{-4}\ \mathrm{N\cdot m}$
Equivalent Young modulus	E	236 MPa	147 MPa
Constant EIBM at +2V	M_e^+	0.029 mN·m	0.127 mN·m
Constant EIBM at −2V	M_e^-	–0.036 mN·m	–0.082 mN·m
The mean absolute value of constant EIBM	$\frac{M_\mathrm{e}^+ - M_\mathrm{e}^-}{2}$	0.032 mN·m	0.104 mN·m
The mean absolute value of constant EIBM normalized to the width of the sheet	$\frac{M_\mathrm{e}^+ - M_\mathrm{e}^-}{2\cdot w}$	2.95 mN	9.47 mN

5 Energy per IPMC sheet area

Let us consider an actuator described in section 2. EIBM $M_\mathrm{e}(s)$ may vary within bounds $M_\mathrm{e}^+(s)$ and $M_\mathrm{e}^-(s)$. $M_\mathrm{e}^+(s)$ and $M_\mathrm{e}^-(s)$ are EIBM-s corresponding to maximal electrical stimulations with the opposite polarities. Let $[p_1, p_2]$ be the working section of the actuator (see figure 2). In this study we concentrate on the length of the working section. Position of the working section is assumed to be selected optimal with respect to the performance of the actuator. Position of the optimal working section can be easily moved by rotating the contacts.

In this section we find the maximal magnitude of force that can be applied in $[p_1, p_2]$, the mechanical work done by the actuator in the working section and normalize it to the area of the IPMC sheet. For simulations parameters R, l, $k_0(s)$, D given in section 4 are used. For graphs of $M_\mathrm{e}^+(s)$, $M_\mathrm{e}^-(s)$ please refer to [3]

5.1 Maximal magnitude of force

Let $G(p_2 - p_1)$ be maximal magnitude of force, that can be applied in both directions within $[p_1, p_2]$.

Let output forces resulting from EIBM $M_\mathrm{e}^+(s)$ and $M_\mathrm{e}^-(s)$ be $F^+(p)$ and $F^-(p)$ accordingly. $F^+(p)$ is the maximum magnitude of force that can be applied in the positive direction and $-F^-(p)$ is the maximum magnitude of force that can be applied in the negative direction. Formal definition of $G(p_2 - p_1)$ is

$$G(p_2 - p_1) = \min_{p\in[p_1, p_2]}\left(\min\left(F^+(p), -F^-(p)\right)\right) \tag{1}$$

As mentioned before, p_1 and p_2 are optimal with respect to $G(p_2 - p_1)$. The constraint is expressed formally as

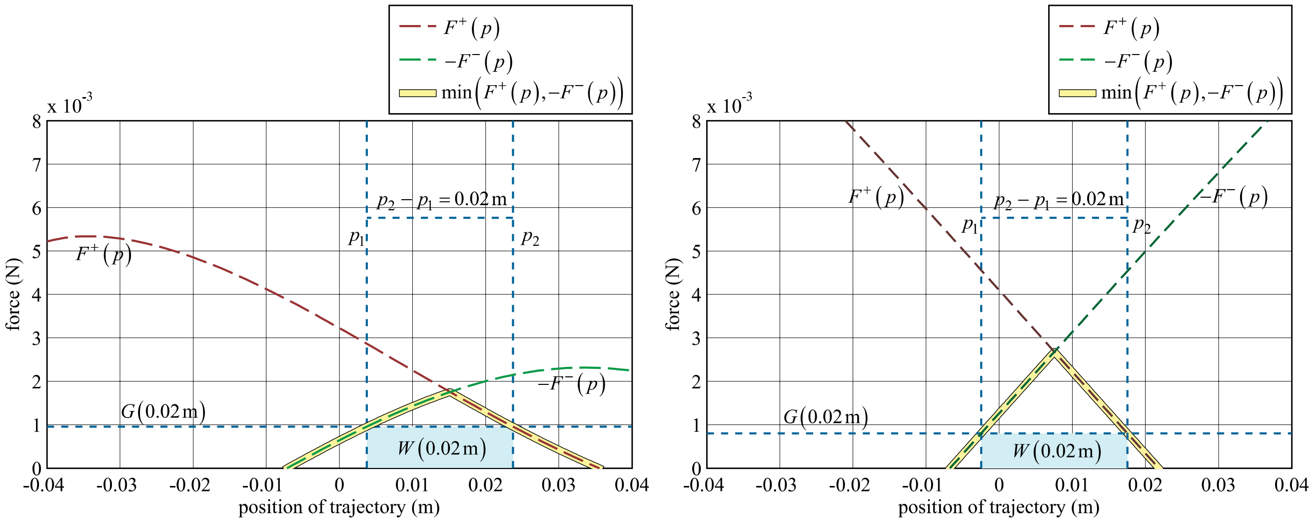
$$\begin{aligned}&\forall\tilde{p}_1\forall\tilde{p}_2\quad(\tilde{p}_1 - \tilde{p}_2 = p_2 - p_1)\Rightarrow\\&G(p_2 - p_1) \geq \min_{p\in[\tilde{p}_1, \tilde{p}_2]}\left(\min\left(F^+(p), -F^-(p)\right)\right)\end{aligned} \tag{2}$$

If $F^+(p)$ and $F^-(p)$ are decreasing functions, it holds that

$$G(p_2 - p_1) = F^+(p_1) = -F^-(p_2) \tag{3}$$

Ability to apply force with magnitude $G(p_2 - p_1)$ is only guaranteed in static equilibrium. In the case the sheet is moving some of the force is spent on overcoming inertial and drag forces.

In figure 3 forces $F^+(p)$ and $F^-(p)$ corresponding to the long and the short sheet are presented. As an example $G(0.02\,\mathrm{m})$ is revealed. In figure 4 the maximal magnitude of force applied in both directions with different lengths of working section for the long sheet and the short sheet is presented.



(a) (b)

Figure3. Forces of long sheet (a) and short sheet (b).

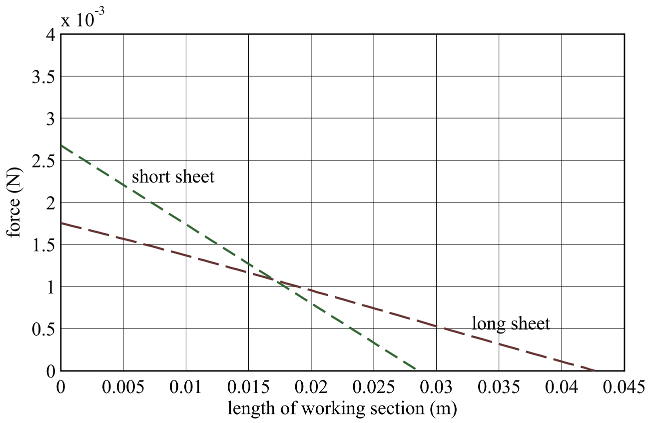


Figure 4. Maximal magnitude of force of the actuators.

Note that the short sheet applies more force in short working sections. It can be explained by the fact that EIBM of the long IPMC sheet decreases in the direction away from the contacts [3].
The length of the working section is limited by the physical properties of the actuator. The longer is the free bendable IPMC sheet, the longer is the working section.

Similar to $F^+(p)$ and $F^-(p)$, also $G(p_2 - p_1)$ is proportional to the width w of the IPMC sheet.

5.2 Energy

Let $W(p_2 - p_1)$ be maximal mechanical work (energy) that can be done by the actuator by traversing $[p_1, p_2]$ with constant force. As $G(p_2 - p_1)$ is maximal magnitude of force that can be applied, it holds that

$$W(p_2 - p_1) = G(p_2 - p_1) \cdot (p_2 - p_1) \tag{4}$$

As the ability to apply force with magnitude $G(p_2 - p_1)$ is only guaranteed in static equilibrium so $W(p_2 - p_1)$ is the capacity of quasi-static work. In case the sheet is moving some of the energy is spent on overcoming inertial and drag forces.

In figure 3 energy $W(20\,\text{mm})$ is equal to the area of the rectangle below the curve $\min\left(F^{+}(p), -F^{-}(p)\right)$. Energy of the two actuators with different lengths of working sections is presented in figure 5.

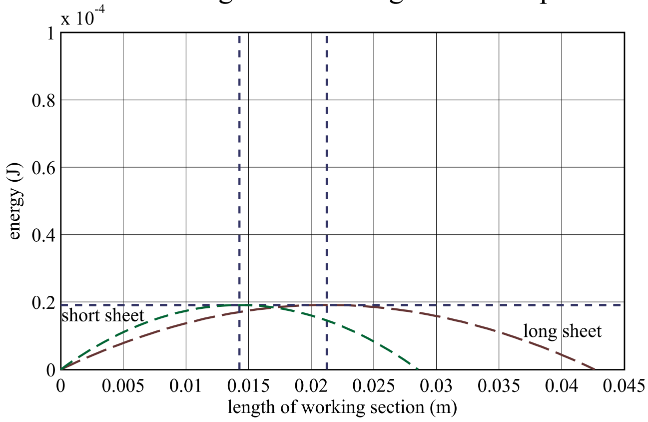


Figure 5. Energy of the actuators.

Note that incidentally the maximal energy of the long and short sheet is about the same. The optimal length of the working section is, however, different.

Similar to $G(p_2 - p_1)$ also $W(p_2 - p_1)$ is proportional to the width of the IPMC sheet.

5.3 Energy per IPMC sheet area

Energy per area S of IPMC piece is defined by

$$A(p_2 - p_1) = \frac{W(p_2 - p_1)}{S}, \tag{5}$$

where in our case

$$S = (l + l_{\mathrm{c}}) \cdot w \tag{6}$$

For 17mm long working section the maximal force applied by the actuator as well as the energy is the same for the long and short sheet. In practice, where the designer has to make a choice which actuator to use, the long sheet can be preferred because of the mechanical simplicity but the elongated short sheet is superior because it contains less expensive electroactive material and therefore consumes less energy. Elongated short sheet has also linear behaviour and would be easier to control.

In figure 6 energy per area of IPMC sheet with different lengths of working sections is presented.

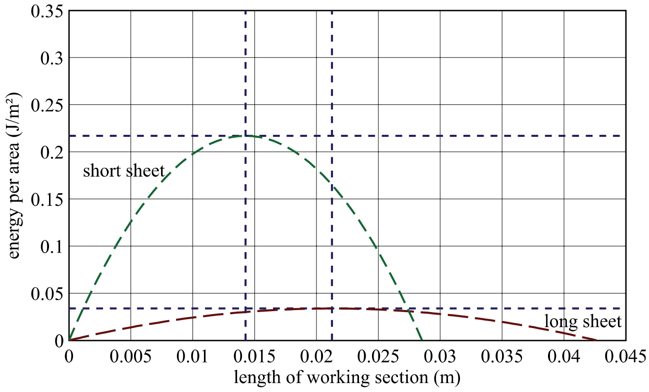


Figure 6. Energy per area of IPMC sheet of the actuators.

Note that maximal energy per area of the long sheet is about 5 times smaller that that of the short sheet.

6 The effect of the rigid elongation

For the actuators with parameters presented in section 4, the maximal energy per IPMC area of the long sheet is about 5 times smaller than energy per area of the short sheet. It is partly because EIBM of the long IPMC sheet decreases in the direction away from the contacts [3] and because the long IPMC sheet is stiffer (see table 3). To understand how the elongation affects the sheet properties we are presenting simulation results with constant EIMB-s and equal stiffness for both sheets.

Table 4 lists parameters of the new actuators used in this simulation. The stiffness D of both new IPMC sheets has the same value as the short IPMC sheet and M_e^+, M_e^- correspond to the mean absolute value of the EIBM of the short IPMC sheet (see table 3). The parameters R and l_c have the same value as specified in section 4. New actuators are identified by the length of the freely bending IPMC part. In case of the new long sheet $l = 0.05\,\text{m}$ and in case of the new short sheet $l = 0.0045\,\text{m}$.

Table 4. Parameters of new actuators.

Parameter	Notation	Value
Initial curvature	$k_0(s)$	$0\ \text{m}^{-1}$
Beam stiffness	D	$1.21\cdot10^{-6}\ \text{N}\cdot\text{m}^2$
EIBM at positive voltage	M_e^+	$0.104\ \text{mN}\cdot\text{m}$
EIBM at negative voltage	M_e^-	$-0.104\ \text{mN}\cdot\text{m}$
Radius of trajectory	R	$0.04\,\text{m}$
Length of the part of the IPMC sheet that is fixed	l_c	$0.0035\,\text{m}$
Width of the IPMC sheet	w	$0.011\,\text{m}$

In figure 7 forces $F^+(p)$ and $F^-(p)$ corresponding to the new long and the new short sheet are presented. In figures 8, 9 and 10 parameters of the new actuators are presented.

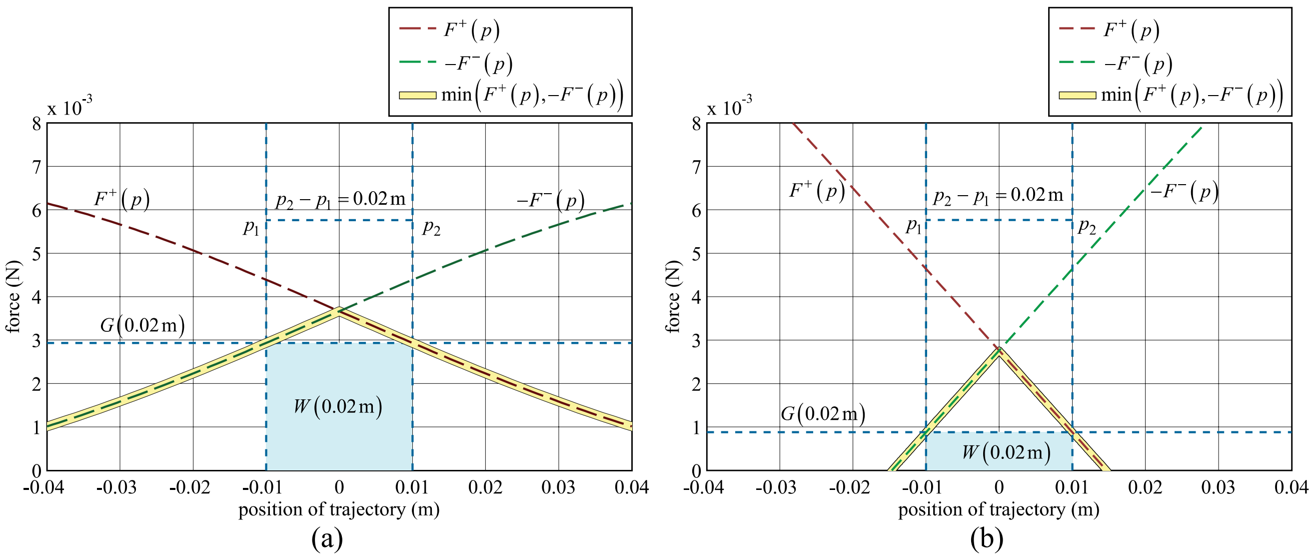


Figure 7. Forces of new long sheet (a) and new short sheet (b).

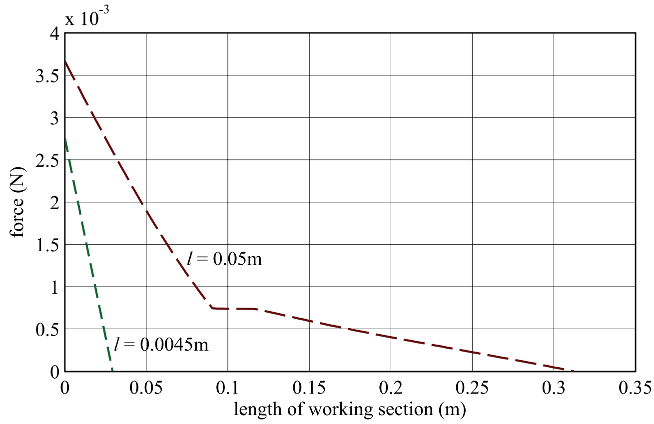


Figure 8. Maximal magnitude of force of the new actuators.

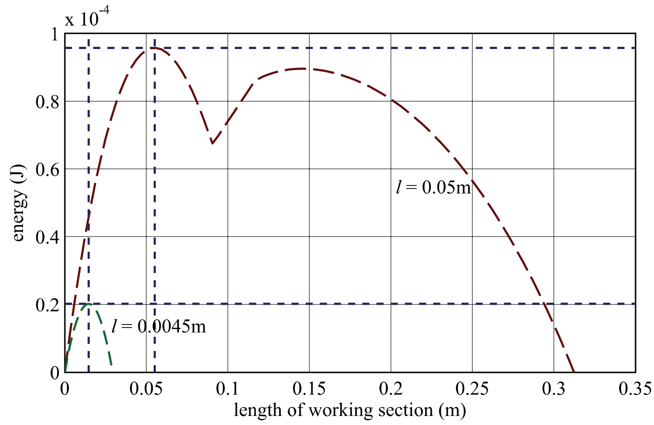


Figure 9. Energy of the new actuators.

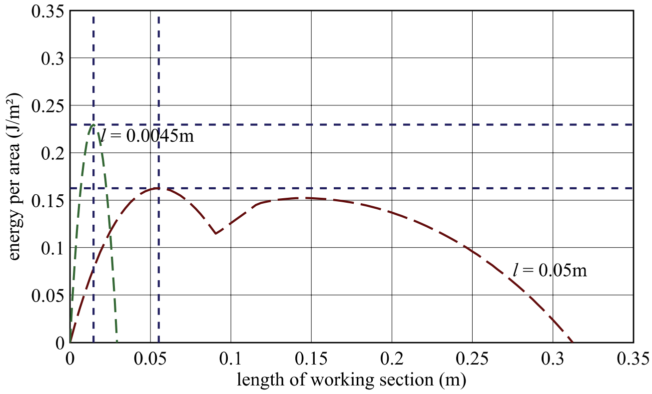


Figure 10. Energy per area of IPMC sheet of the new actuators.

The properties of the new and the old short sheet are approximately equal. As the new sheet is symmetric, the center of the working section is now at position zero. Small initial curvature and difference in absolute values of EIBM-s corresponding to opposite electrical stimulations does little else than shifts the working section (see figure 7).

These simulations show that the new long sheet is much more capable than the old long sheet and both the new and the old short sheet. Maximal length of working section has increased as well. Energy per area of IPMC sheet of the new long sheet is however still notably smaller then that of the short sheet. We thus conclude that elongation as construction element can be used to increase energy per area of IPMC sheet.

7 Optimal design

The model introduced in section 2 enables us to find the minimal area of an IPMC sheet, capable of applying a predefined force within a predefined working section. As the force per area of the sheet does not depend on the width w of the sheet, the required parameter is the optimal length l of IPMC sheet. After the optimal length is found, the width of the sheet can be chosen according to the required output force.

The optimal length is a function of the length of the working section. For illustration purposes simulations with parameters listed in table 4 are conduced. For different values of l energy per area is found. In figure 11 the optimal length of the freely bending IPMC sheet for maximal energy per area is presented. In figure 12 the corresponding energy per area is presented. The maximal energy per area corresponds to 0.050m long working section and 0.019m long freely bending IPMC sheet.

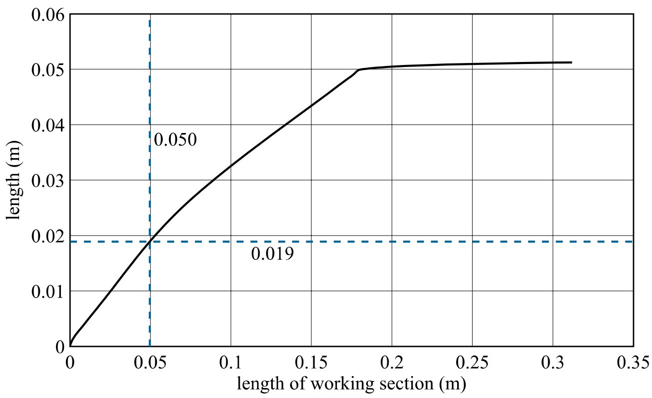


Figure 11. Optimal length.

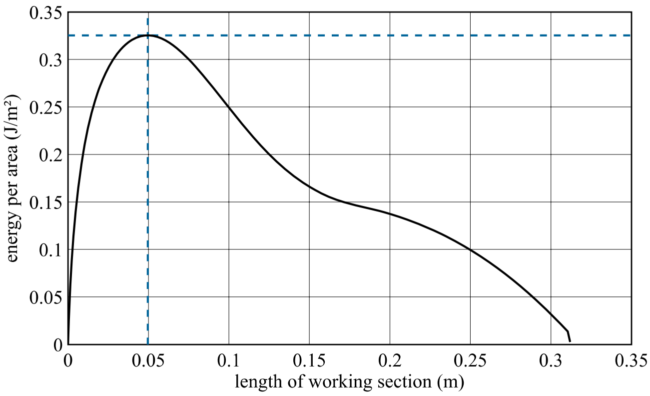


Figure 12. Maximum energy per area of IPMC sheet.

8 Conclusions

In this paper we have shown that the required output force determines the width of the sheet. The length of the free bendable IPMC part is determined by the required length of the working section.

We also present a method for finding an optimal design of an IPMC actuator. The actuator is in a cantilever beam configuration and can have a rigid elongation. We have optimised the actuator configuration by maximizing mechanical work per sheet area.

We conclude that a rigid elongation can be used to increase the performance of the IPMC sheet.

Acknowledgements
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