**Back-relaxation of IEAP actuators.**

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**Abstract** tuleb alles siis kui conclusion on valmis.

Already since the very first reports about the ionic electroactive polymer actuators, the researchers have described the „back-relaxation“ effect – an actuator excited with DC voltage, instead of holding its bent state, relaxes slowly back towards its initial shape, eventually reaching its equilibrium, but seldom attaining its initial state. This behavior is commonly treated as a shortcoming of IEAP actuators, decreasing their ability to deliver a constant peak force to target, limiting their frequency range, and hindering their exact control. There have been several attempts to slower the rate of back-relaxation by choosing an opportune combination of separator, electrodes, and mobile ions. Nevertheless, there is no report claiming that in the case of some IEAP material this holdback is completely eliminated.

Supposedly the phenomenon of back-relaxation is studied almost only in the case of „old-type“ ionic polymer-metal composites (IPMC). It is a wet ion exchange polymer membrane covered with thin metal electrodes on both sides. [X7] For typical IPMC with platinum electrodes, when a voltage is applied across the thickness direction, the electromechanical transduction occurs due to the motion of the cations along with the water molecules. As a result, one face of IPMC withers and shrinks and the opposite face protracts due to swelling with water and ions. This generates warping of the whole laminate. The resulting fast bending motion toward the cathode is followed by a slow relaxation towards the anode, while IPMC as the whole still remains bent. The speed of back-relaxation is reported being dependent on the type of polymer membrane, solvent, cations, etc. [X6]. It is commonly believed that the slow relaxation happens due to the water diffusion out of the strained polymer matrix. [X7]

In order to diminish or slow down the back-relaxation, several different approaches have been described. One may even intuitively guess that thicker IPMC, or IPMC containing viscous liquid are more stiff and exhibit less back-relaxation [X1], however these remedies pull down the working frequency of the resulting device. Kim et al [X2] report that the palladium buffer layer below the platinum electrode improves the performance of IPMC, including the noticeable abatement of the back-relaxation. Some authors suggest using TBA as cations [X11] or different membranes. [X4,X5, X10] …..

In recent years the range of IEAP materials has been significantly extended by means of materials used for electrodes, separator membrane, as well as the electrolyte. At first glance, all ionic EAPs seem similar in construction – two conducting electrodes separated by a polymer membrane, containing freely moving ions – but their actuation mechanisms can be significantly different. There haven’t appeared any definitive models or reports yet describing the phenomenon of back-relaxation of IEAP actuators with electrodes based on carbon, or conductive polymers.

There have been proposed several different electromechanical models describing the behavior of IPMC, most of them just neglect the phenomenon of back-relaxation. [XXX] One of the few is presented by Bao et al. [X3] proposing the model of IPMC without and with the back-relaxation by adding a separate relaxation time constant. [X8] kirjeldab ka midagi

Performing our experiments with IEAP actuators of different types, we have noticed that similarly to the water-containing IPMC, to some extent several of them exhibit back-relaxation. It appears that by means of their transient spatial actuation and transient moment of force, the long-term behavior of virtually all IEAP actuators is just similar. This action is present regardless of the absence of the fluent liquid, and is not contingent of the materials of the membrane or electrodes.

The objective the current paper is describing the time-dependent correspondence between the transient input voltage and the shape of the actuator, taking into account also the back-relaxation. We ground to the scalable distributed model of IPMC, presented by Punning et al. [X9], and extend it to different IEAP materials. According to this approach, an IEAP actuator in a cantilever configuration resembles a lossy RC transmission line. The transient behavior of voltage is commonly uneven, and is determined by a set of measurable electrical parameters of the material – conductivity of the electrodes and impedance of the membrane. As the propagation of the electrical signals along this circuit is determined by a simple pseudo-parabolic PDE, it is easy to calculate the the instantaneous values of the coordinate-dependent voltages, charges, etc. numerically or even analytically. The electromechanical coupling between the electrical input signal and the flexure of the actuator is determined by the time- and coordinate-dependent charge carried over between the two electrodes. The experiments described in [X9] assume that the charge-flexure relation is simply linear, and leave off just before the phenomenon of back-relaxation becomes noticeable.

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X1: doi: 10.1117/12.654740

X2: doi:10.1088/0964-1726/17/3/035011

X3: doi: [10.1117/12.475167](http://link.aip.org/link/doi/10.1117/12.475167)

X4: doi: 10.1002/marc.201100535

X5: doi: 10.1002/pen.21955

X6: doi: [10.1063/1.2194127](http://link.aip.org/link/doi/10.1063/1.2194127)

X7: doi:10.1088/0964-1726/20/8/083001

X8: doi: [10.1117/12.475201](http://link.aip.org/link/doi/10.1117/12.475201)

X9: PunnDistrModel

X10: doi: 10.1021/ma800956v

X11: Spie 2002 - 4695-33

Electro-active polymers or EAPs are materials that change their shape and size when electrically stimulated. As both actuators and sensors they are considered attractive for various applications in e.g. biomedicine and robotics. Roughly EAPs can be divided into dielectric and ionic actuators. In this work the focus is on ionic EAPs. The state of art of EAP devices is reached the level of the first commercial outputs of EAP actuators, e.g. the ViviTouch tactile feedback system taking the gaming experience of mobile devices to the next level and Optotune’s electrically tuneable lens.

Although there are some commercial products of the EAPs, there is still much research to carry out. Whereas the bending motion of described actuators is easily attainable, it is rather complicated to estimate that bending motion and control the system precisely. Already some decent models have been developed to describe the tip displacement{{1085 Bhat,N.D. 2004}} or the blocking force for instance. In the models currently available, several assumptions are made which are more or less limiting the usability of the models.

One possible approach to model the behaviour of an EAP is using curvature and bending moments along an actuator. Anton *et al* added an elongation to an IPMC actuator and constructed a mechanical model. One important conclusion of their work was that the distribution of an EIBM (Electrically Induced Bending Moment) is not constant along the actuator i.e. the deflection of the actuator is growing faster near contacts and slower by moving away from contacts. The reason of this effect is the combination of high electrode resistance and high capacitance of the composite.

D:\doktorantuur\joonised\1mm_3positions_CPC_3V.tif Similar behaviour is occurring in carbon polymer composites (CPC) – a composite material made of polymer membrane, carbon electrodes and ionic liquid. Although the electrode conductance have been improved by laminating an extra layer of highly conductive metal (e.g. gold), several issues arise. First of all, it is complicated to obtain a highly durable bond between metal layer and carbon electrode. Secondly, the composite becomes unusable in applications where avoidance of metals is compulsory. Therefore, it is not possible to consider the radius of curvature as a constant and distributed model of curvature is essential for accurate estimations.

Punning et al introduced the correspondence between IPMC (ionic polymer metal composites) and a RC transmission lines. It appears that the voltage distribution along the IPMC actuator can be expressed similarly as RC lines. Although there was noticeable linear correlation between the charge and the curvature, it was validated in a short time frame, thus neglected the back-relaxation phenomena – first the actuator exhibits quick motion after which it slowly restores its initial state. Therefore it is important to consider back-relaxation for accurate modeling in a long time perspective.

In previous work the relaxation has been expressed by fitting tip displacement with multiple exponential decay terms{{1085 Bhat,N.D. 2004}}, modelling creep in closed loop control systems[].

The objective of the work is to obtain the time-dependent correspondence between the transient input voltage and the shape of the actuator. Similarly to the model of Punning, we consider EIBM to be a linear function of distributed charge. Additionally, the back-relaxation phenomenon is modeled completing the model for long time actuations. Compared to most of the models developed so far, the distributed curvature analysis adds the possibility to estimate the shape of the actuator much more precisely.

**Mechanical model**

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**Fig. 1**

Vektori pikkus, põhjendus.

Because of the transient approach of the current model, we can take an advantage of the Euler-Bernoulli beam theory (1) to relate bending moments and curvature.

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is the bending stiffness, is the effective modulus of elasticity and is the second moment of area. In this paper the cross-section of the beam is a rectangle, thus, where and are width and height of the cross-section of the beam respectively.

Although the complete model is able to consider the own weight of the IEAP, it is neglected in this paper by placing the actuator such that gravity vector and shape of the IEAP are always perpendicular.

3d pilt pingest, laengust ja tegelikust liigutusest

**Model description**



Throughout the time, the response of polymers has been described with large variety of models. One of them is Kelvin-Voigt model which is composed of a spring and a dashpot connected in parallel [response of polymers book]. To describe whole actuation process of the IEAP with relaxation included, we have modified Kelvin-Voigt model by adding an external strain component in series with the dashpot (FIG2). Although the certain similarity with Kelvin-Voigt model preserves, the model acts in a completely different way. The definition of the model is summarized with the relations (1), where is the strain of a dashpot, is the strain of a spring and is an externally applied strain. and are balancing stresses on dashpot and spring respectively. The constants and are the modulus of elasticity of the spring and the viscosity of the dashpot correspondingly.

The model behaves as indicated in Fig. 2. First, let us consider the model in a neutral state i.e. a state where (Fig.2a). If a change in Q occurs, the strain of the spring directly follows the external strain from Q (Fig.2b). Strain changes in the spring initiates stress which in turn affects the dashpot causing the spring to relax to its initial position (Fig2.c).

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Fig. 2 Electro-mechanical model in neutral state (a), excited state with constant charge (b), and relaxed state (c) with charge still applied.

Combining the relations (1) leads to a differential equation of the model is obtained.

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The solution for this first order linear differential equation with homogenous boundary condition is given by:

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Introducing the rate of relaxation , and using , takes us to the equation.

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**Experimental setup**

The actuation process of a carbon polymer composite (CPC) material was observed visually from side. The shape of the actuator was recorded by CCD camera (Pointgray) at 10 frames per second. Grabbed video was processed several image processing operations to obtain the vector representation of the actuator. Assuming that the curvature remains constant in between the end points of each vector, the curvatures for each vector were determined. All the tasks from signal generation up to the post processing of the curvature changes were carried out with NI LabView software with Matlab engine for numerical model evaluations as indicated in fig 1.

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Fig. 3 Experimental setup overview.

In this work, we assume that the EIBM is linearly depending on charge by a coefficient. After this assumption, from classical beam theory we have

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where is the second moment of area and is half of the height of the beam. Denoting we can rewrite the equation 4 as equation 6.

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The curvature can be also presented in Cartesian coordinates as:

where and are the initial position of the curve and the angle

where is initial angle at s=0.

The four input parameters of the distributed RC model were found using the differential evolution (DE) optimization algorithm minimizing the differences between measured and calculated voltages between the electrodes along the actuator. The DE algorithm is genetic type algorithm that combines and rearranges parameter vectors. The algorithm is converging fast and is effective for solving problems with multiple local minimums as this particular task is.[Viide]

The value of was determined directly from eq. 1 by neglecting the existence of the back-relaxation component near. Rewriting eq. 5 for leads to eq. 6. To avoid numerical errors

**Results**

The parameter was derived from eq. 5 and was evaluated in region.

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| |  |  | | --- | --- | | Parameter | Value | |  |  | |  |  | |  |  | |  |  |   **Table 1. Measured parameters for CPC actuator.** | **Fig. 4 Measured and simulated voltage along the actuator at 2.0 V step input signal.** |

As seen in figure 1, good correlation between experimental data and simulated data with optimized parameters was obtained.

The simulated points are clearly following the actual shape of the actuator. The shape of the actuator

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| Fig. 5 Measured and modelled shapes of the actuator at 2.5V. | Fig. 6. Measured and modelled shapes of the actuator at 2.5V |

**Conclusion and discussion**

**Acknowledgments**

References

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