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 the most studied 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] Voltage applied between the conductive electrodes causes migration of the solvated ions between the electrodes. 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. 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. 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 backrelaxation 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 exhibits less back-relaxation, [X1] however this remedy affects the behavior, e.g. 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 describe …. to choose appropriate cations [] or membranes. [X4,X5] …..

There have been proposed several different electromechanical models describing the behavior of IPMC, most of them just neglect the phenomenon of back-relaxation. [XXX] Nevertheless, [X3] gives the model of IPMC without and with the back-relaxation. The difference stands in the presence of the separate relaxation time constant. [X8] kirjeldab ka midagi

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.

Performing our experiments with IEAP actuators of different types, we have noticed that similarily to the water-containing IPMC, virtually all of them exhibit back-relaxation,. It appears that regardless of the absence of the fluent liquid, and not contingent of the materials of the membrane or electrodes, the long-term behavior of all actuators is similar by means of their transient spatial actuation and transient moment of force. The difference stands solely in the time constants of faster forced bending and slower back-relaxation. Dividing the lon-term bending movement of an IEAP actuator into two components – transient voltage-induced actuation, and transient back-relaxation results with a model, suitable for all of them …..

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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

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**

Momentidega joon koos lihase oma raskusega.

Vektori pikkus, põhjendus.

Oma raskus=0 ja edasi ei arvesta

3d pilt pingest, laengust ja tegelikust liigutusest

**Model description**

The key component of the mechanical model is time dependent and coordinate dependent charge. This charge initiates internal stresses and results bending motion of the material. The model consists of two parts: an electrically induced quick bending that produces electrically induced bending moment (EIBM) followed by slow relaxation described through back-relaxation bending moment (BRBM) – a bending moment opposite to EIBM. For the sake of simplicity let us assume that the charge and EIBM is in linear relationship with coefficient .

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The relaxation of the actuator can be also expressed in terms of charge with an additional exponential member (eq. 2). This equation is very similar to the Kelvin-Voigt model which has been used to model creep of polymers. The difference lies on the argument of exponent where linear time component is replaced by an integral of charge over time. Notice that from the time charge has reached its maximum value i.e. charge is constant in time, the presented integral is simply growing linearly in time like the argument of exponent in Kelvin-Voigt model. Similarly to Kelvin-Voigt model we have accommodated the parameter that denotes the rate of relaxation and is expressed by, where and are the modulus of elasticity and viscosity of the material correspondingly.

**Int=f(s,t)**

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Combining eq. 1 and 2, the total bending moment is given by:

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The Euler-Bernoulli beam theory relates bending moments and curvature as :

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

Denoting and substituting eq. 3 into eq. 4 we can now write the equation for curvature:

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where is the initial curvature of the actuator.

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.

**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 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. 1 Experimental setup overview.

The four input parameters of the distributed RC model were found using the differential evolution (DE) optimisation algorithm minimising 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.

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. 2 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 optimised 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. 3 Measured and modelled shapes of the actuator at 2.5V. | Fig. 4. Measured and modelled shapes of the actuator at 2.5V |

**Conclusion and discussion**

**Acknowledgments**

References

[1] Chenying Yang, Wei Wang and Zhihong Li, "Optimization of corona-triggered PDMS-PDMS bonding method," in *Nano/Micro Engineered and Molecular Systems, 2009. NEMS 2009. 4th IEEE International Conference on,* 2009, pp. 319-322.