A software tool to estimate the dynamic behaviour of the IP²C samples as sensors for didactic purposes

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Abstract. Ionic Polymer Polymer Composites (IP²Cs) are emerging materials used to realize motion actuators and sensors. In the former case a voltage input is able to cause the membrane to bend while in the latter case by bending an IP²C membrane, a voltage output is obtained.

In this paper authors introduce a software tool able to estimate the dynamic behaviour for sensors based on IP²Cs working in air. In the proposed tool, geometrical quantities that rule the sensing properties of IP²C-based transducers are taken into account together with their dynamic characteristics. A graphical interface (GUI) has been developed in order to give a useful tool that allows the user to understand the behaviour and the role of the parameters involved in the transduction phenomena. The tool is based on the idea that a graphical user interface will allow persons not skilled in IP²C materials to observe their behaviour and to analyze their characteristics. This could greatly increase the interest of researchers towards this new class of transducers; moreover, it can support the educational activity of students involved in advanced academical courses.

1. Introduction

Ionic Polymer Polymer Composites (IP²Cs) are made of innovative materials: an ionic polymer membrane and an organic conductor deposited on both its sides. They can work either as low-voltage-activated motion bending if an electric field is applied across their thickness or as motion sensors generating a detectable voltage if subjected to a mechanical deformation [1]. Moreover, IP²Cs combine electro-mechanical coupling capability with some very interesting properties when working either as actuators or as sensors (such as low required voltage, high compliance, lightness, softness and so forth).

Starting from IPMC [2][3] transducers study, their structure has been modified substituting the metal electrodes with organic conductor ones.

Like for IPMC devices, a fluorocarbon membrane, Nafion®117, is the core of IP²Cs. It has been subjected to a sandblasting process in order to ensure the electrode mechanical adhesion, and to a cleaning process by both ultrasonic and chemical cleaning (by boiling HCl (2.5 M) and by boiling water).

Then the IP²C membranes have been realized by covering Nafion® 117 sheets with an organic conductor in order to realize the complete device.

This electrode substitution has permitted to manufacture totally organic transducers by using easier, cheaper and faster techniques than those needed for IPMC realization. Different organic conductors
have been used for IP²C realization and obtained samples have been investigated [4] and compared in order to give high performances. Starting from the obtained results, the employed sample to perform sensor model has been realized by covering Nafion® membranes with PEDOT:PSS (Orgacon™ EL-P 3040) conducting polymer as electrode material. The membrane electrodes have been deposed by drop-casting technique which has provided satisfactory performances. The application fields of such devices are different, such as robotics, aerospace, biomedics [5], etc.

In this paper authors propose a software tool which allows the estimation of the behaviour of the IP²C when working as sensor. A Graphical User Interface (GUI) has been developed in Matlab® to provide seamless integration with the mathematical model of the IP²C sensor. The software tool estimates the sensing current of the IP²C when a deformation is applied. In particular, the user can change the dimensions of the simulated sample and the input deformation.

A variety of didactic situations has been focused by the authors in the last years. Indeed, different tools have been presented, which have been implemented in order to solve specific problems: in particular, different typologies of students, involved in different experimental training, have been considered. Didactic activities have been oriented to visual impaired people and also to the undergraduates. Some fundamental measurements problems have been taken into account, as well as advanced software and instrumentation. Some meaningful examples are reported in [6] [7]. The developed tool could be valuable to support the educational activity of students involved in advanced academical courses.

In the next session the IP²C as a sensor and a brief introduction to the used model will be presented. The model has been determined according to the physical phenomenon involved in the electromechanical transduction and assumes the form of differential equations. Section 3 reports sensor software description developed by authors. In section 4 and section 5 some considerations and conclusions are drown.

2. The model of the IP²C sensor

The sensor model predicts a sensing signal corresponding to the mechanical applied stimulus. A linear model for IP²C sensors was suggested in [4] and was based on the Euler-Bernoulli theory of the pinned beam and an adaptation of the theory of the piezoelectric coupling effect [8]. A set of relationships can then be derived between the mechanical stimuli applied and the electrical reaction produced. In Figure 1 a scheme of the configuration used to model the IP²C working as a sensor is presented. The sensor model is scaled as a function of the relevant parameters. In particular, the influences of length, thickness and width characterizing the IP²C samples have been considered. These parameters can be completely chosen by running the user friendly software described in the next section. As reported in Figure 1, the quantities involved in the model are: the imposed mechanical deformation \( \delta(t) \), the output sensing signal (in the model it is represented by a short circuit current \( I_{sc}(t) \)) and the parameters that can be changed by the user in accordance with the feature size of the sample, as mentioned before.

![Figure 1. A scheme of the mechnano-electrical model adopted to describe the sensing behaviour of the membrane.](image-url)
Equation (1) defines the relationship between the imposed deformation and the sensing current, this expression has been used as sensing model implemented in the simulation software. The quantities \(d(s)\) and \(Y(s)\) are functions of the frequency domain which model electromechanical transduction features of the polymeric materials, and the quantities \(th, w, Ls\) are feature size characterizing the device.

3. IP\(^2\)C Simulation Software

To allow users to investigate the mechanical and electrical behaviour of IP\(^2\)C sensors, a Graphical User Interface (GUI) has been produced. This has been developed in Matlab\(^\circledR\) to provide seamless integration with the mathematical models of the IP\(^2\)C sensor introduced in section 2. As it is known, Matlab\(^\circledR\) is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis and numeric computation; it allows to develop a wide range of applications, such as implementation of mathematical models for engineering applications. A piece of the implemented model is reported in appendix A, where some simple instructions are listed for IP\(^2\)C sensor model performed. It also lets to easily build GUI that allows to improve the interaction with the user: in this application the sensor simulation interface allows the user to change the dimensions of organic transducers and to view the result graph. The software in also used for didactic purposes, in order to attract the attention of the students on this environment.

The input signal for deflecting the sensor can also be specified: sinusoidal, sweep, step, square or user defined by uploading a file containing the samples of the desired signal to force. Figure 2 reports the four feasible selections of input deflection that allow the user to see and to analyze sensor behaviour varying input signal. Every signal is characterized by some parameters, such as frequency, amplitude and duration, according to the selected type signal.

![Figure 2. Simulated input deflections applied to IP\(^2\)C sensor model.](image)

The resulting behaviour of the sensor can then be studied in order to analyze the characteristics of these organic transducers.

The parameters describing the geometrical model of the IP\(^2\)C are shown in Figure 3 and include the width (\(w\)), free length (\(Lt\)), active length (\(Ls\)) and the clamped length (\(Lc\)).

The user can modify these values through the software interface in order to evaluate the variation produced on the behaviour of the sensor.

The thickness of the IP\(^2\)C (\(th\)) includes both the Nafton\(^\circledR\) and two electrodes layers thicknesses. It is fixed at 200 \(\mu\)m.
3.1 The sensor’s software to estimate the sensing signal

The GUI uses the information chosen by the user to load from a database relevant quantities, that characterize the model of the IP2C sample. In particular the database contains the parameters values characterizing IP2C (e.g. piezoelectric function, Young’s modulus, etc.) that combined with the user specifications are used to compute the sample models.

This database is the core of the simulation tool and stored information has been collected by executing a large number of measuring surveys. The GUI has been designed to allow future addition to the database of information for new IP2Cs, as soon as they are available, ensuring the software tool remains versatile.

The variables $L_t$, $L_s$ and $w$ can be modified, while $L_c$ is not used in the model. In fact, the mechanism involved in the production of the sensing signal depends on the section of the membrane subjected to a curvature. The length of the clamp is neglected because it does not produce any contribution to the sensing signal. $L_s$ is the point where the mechanical stimulus is applied to membrane. $L_t$ represents the free length of the cantilever beam, this feature size must be higher than $L_s$.

Figure 4.(a) represents the software tool simulating the response of the membrane when a sinusoidal deformation with amplitude about 1mm peak-to-peak and frequency 10 Hz is applied. In this case the short-circuit current is estimated.

The response of the software has been confirmed by the experimental surveys performed with real membranes. In fact, Figure 4.(b) shows the short circuit current produced when a sinusoidal mechanical deformation with the same frequency and amplitude of previous simulation is applied to IP2C membrane.

The feature sizes of device are $L_s=13$mm and $w=5$mm, thus obtained current can be compared to simulation results.

![Figure 3](image-url)  
Figure 3. Feature size of IP2C sample.

![Figure 4](image-url)  
Figure 4. Software simulation of sensor with a sinusoidal input signal (a) and experimental data imposing the same deformation to a membrane (b).
4. Discussion
The developed software allows to analyze and simulate some peculiar characteristics of organic sensor. In fact, through the simulation tool it is possible to perform the following tasks:

- definition of the model used to describe the behaviour of the device under investigation;
- study of the relation between imposed displacement and the correspondent electrical response;
- investigation of the device performances (as a function of geometrical and electrical parameters) such as operating range, mechanical sensitivity, resolution, time response and other specific analysis by exploiting graphic representation of such quantities as a function of device parameters;
- simulations of the device behaviour taking into account also different forced displacement.

![Figure 5. Help window opened through the help button located on the user interface.](image)

Another necessary consideration is about use and management of IP$^3$C sensor software. In fact, a help button allows to obtain some knowledge both about the organic transducer and the tool use. Figure 5 shows the help window in which the user can get the information of interest, through a subject list. Since this software has been implemented for educational use, the help window is a tool capable to provide students the principles of operation of devices based on polymeric materials, other than to assist at correct use of software. Moreover, through the help window it is possible to open a file that explains in detail as the software has been realized and other helpful IP$^3$C characteristics.

5. Conclusion
In the paper an easy to use original software tool has been presented. The software, developed in Matlab®, consists of a database for storing relevant quantities, a set of routines for the simulation of the transducers, and a GUI that interfaces with the user. The key idea of the described software tool is to provide a user-friendly graphic interface which allows persons not skilled in IP$^3$C materials to study their behaviour.

This is a fundamental aspect, especially when the user wants to simulate and understand the dynamic behaviour of the membrane without performing real experimental observations. The proposed software can be used, therefore, as a valuable instrument for the design of devices based on IP$^3$C membranes.

The tool could be valuable in advanced academical courses to support students dealing with the study and the development of organic transducers. In particular, the possibility to understand models describing the device behaviour will help them in the comprehension of mechanisms ruling the behaviour of such devices and their peculiarities.
6. References

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Appendix A. Matlab implementation of IP2C sensor model

The developed tool refers to a function that defines sensor model of organic transducers. The model instructions are shown in the following list.

```matlab
function [sens_curr] = sensor(Ls,w,th,deformation,ts,parameters)
tfo = 0:ts:(length(deformation)-1)*ts;
Y = parameters(1);
k = parameters(2);
a = parameters(3);
d = tf([k],[1 a]);
derivative = tf([1 0],[1]);
sensor = derivative*(3*d*th*w*Y)/(4*Ls);
sens_curr = lsim(sensor,deformation,tfo);
```

In the function `sensor` some simple instructions are used, such as `tf` that permits the creation of transfer functions and `lsim` that allows to simulate time response of linear time invariant models to arbitrary inputs.