**TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE**
MECHANICS | MECHANIKA
1-M/2013

IRENEUSZ DOMINIK*, FILIP KASZUBA*, RENATA DWORNICKA**

# PROSTHESIS DESIGN DRIVEN BY ELECTROACTIVE POLYMERS

# ZASTOSOWANIE POLIMERÓW ELEKTROAKTYWNYCH DO BUDOWY PROTEZ

A b s t r a c t

Applications of dielectric elastomer (DE) actuators are presented in this paper. Dielectric elastomers (a type of electroactive polymer) are one the most promising smart materials. They consist of two flexible electrodes and a dielectric film between them. After applying voltage (3–5 kV) to the electrodes, the thickness of the polymer layer lowers. Changes of the thickness can be indirectly measured , enabling the element to work as a sensor. A self-sensing and energy harvesting elements are also described. Two applications are described – an active orthosis and a force feedback device.

*Keywords*: *dielectric elastomers*, *electroactive polymers*, *smart materials*

S t r e s z c z e n i e

W artykule przedstawione są zastosowania siłowników opartych na elastomerach dielektrycznych. Materiały te są jednym z najbardziej obiecujących przedstawicieli materiałów inteligentnych, a dokładniej – polimerów elektroaktywnych. Składają się z dwu podatnych elektrod i warstwy polimerowego dielektryka pomiędzy nimi. Po przyłożeniu napięcia aktywacji (ok. 3–5 kV) zmniejsza się grubość tej warstwy. Ta zmiana grubości może być mierzona w sposób pośredni, co pozwala na pracę element jako czujnika. Opisano tryb jednoczesnej pracy siłownikowo-czujnikowej i magazynowania energii. Dwa zastosowania zostały szczegółowo opisane: aktywny wyciąg ortopedyczny palca i urządzenie do siłowego sprzężenia zwrotnego.

*Słowa kluczowe*: *polimery elektroaktywne*, *materiały inteligentne*, *elastomery dielektryczne*

* PhD. Ireneusz Dominik, MSc. Filip Kaszuba, AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Department of Process Control.

** PhD. Renata Dwornicka, Institute of Applied Informatics, Faculty of Mechanical Engineering, Cracow University of Technology.

## 1. Introduction

Dielectric elastomers (also called artificial muscles) are materials with a large number of potential applications, ranging from entertainment to medicine and space exploration. Intensive research is conducted worldwide to develop these materials and electroactive polymers in general. This is due to large strain (up to 380%) and very high energy density (3,4 J/g), which is unmatched by any other smart materials such as ferroelectrics and piezoelectrics [[1]].

## 2. Smart polymers

Applications presented in this paper are designed to utilize actuators based on dielectric elastomers, which are a type of electroactive polymers. Polymers are a large group of chemical compounds, many of which are used in everyday life [2]. So called smart polymers (or generally smart materials) have one or more properties (e.g. conductivity, dimensions, elasticity, shape, structure etc.), that can be controlled by an external stimuli such as temperature, acidity, electric or magnetic field, humidity. A smart material responds to these stimuli predictably and in a short time. The response time should be as small as possible.

Smart materials that change their dimensions in response to electrical signal (electroactive polymers, abbreviated EAP) [3] are the most interesting as far as technical applications are concerned. They can be divided into following groups, as proposed by ESNAM – European Scientific Network for Artificial Muscles [4].

- Electro active polymers
  - Ionic polymers
    - Ionic Polymer-Metal Composites
    - Ionic Polymer Gels
    - Conducting polymers
    - Carbon nanotubes
  - Dielectric polymers
    - Dielectric Elastomers
    - Electrostrictive paper
    - Liquid crystalline Polymers

EAP are commonly called artificial muscles, because of their biocompatibility and their force and energy densities similar to skeletal muscles [3, 5]. Presence of an electric field is required for electronic polymers to work, they require high actuating voltage (order of kV), with low current (μA) and do not generate voltage when actuated mechanically. Ionic electroactive polymers depend on an ion flow inside an ion-conducting polymer, require actuating voltage of max. 5 V, current approximately 100 mA. They also exhibit opposite effect – generate voltage while actuated mechanically, thus converting mechanical energy to electrical energy.

### 2.1. Working principle of dielectric elastomers

This is a group of smart polymers that deform under applied electric field [6]. This material consists of a thin layer of dielectric (electrical insulator) polymer and two flexible electrodes. This electrode has to be highly conductive and follow the deformation of an artificial muscle.

After inputting high voltage to the electrodes, the electric force brings the two layers closer, compressing the dielectric film (Fig. 1). Actuation pressure is described by equation 1:

$$p = \varepsilon_0 \varepsilon_r \left( \frac{U}{d} \right)^2 \tag{1}$$

where:

$p$ – actuating pressure
$\varepsilon_0$ – permittivity of a vacuum
$\varepsilon_r$ – permittivity of the elastomer
$U$ – actuating voltage
$d$ – thickness of the elastomer

As seen in the equation 1, actuating voltage should be as high as possible; practically it means that the actuation voltage is close to the breakdown voltage of the dielectric layer, which usually is 3–5 kV. This value is one of the biggest disadvantages of these materials. Thanks to advanced manufacturing technology, the thickness of the dielectric layer can be lowered to the order of single μm, therefore lowering the voltage to a few hundred volts [7]. Electrically, a dielectric elastomer can be described as a flexible capacitor, where flexible electrodes are its plates. A simple actuator can be constructed with widely accessible components. Insulating layers of various elastic moduli, thickness or density are commercially available and can be selected for specific purposes. Various types of stretchable electrodes are proposed, e.g. carbon black, grease, rubber, dust or glue [6].

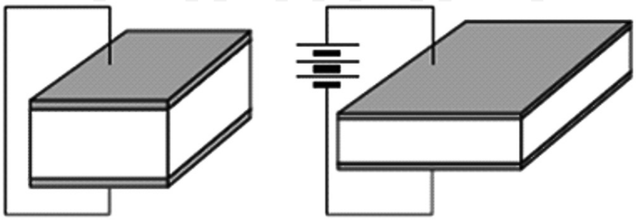

Fig. 1. Mechanical deformation of a dielectric elastomer under DC actuation voltage

Rys. 1. Mechaniczne odkształcenie elastomeru dielektrycznego pod wpływem przyłożonego napięcia

A dielectric elastomer can work in three modes – as an actuator, a sensor and an energy storage device. Sensing is possible through measurement of the capacitance of the flexible capacitor, which is inversely proportional to the distance between the plates. Applying an external force to the element moves the plates closer together. Jung et al. [8] conducted an experiment in which they designed such a system. The flexible capacitor was a part of an analog high-pass filter, and its cut-off frequency was measured. The polymer was powered by an actuating 3 kV DC signal and a 300 V peak-to-peak AC measurement signal. The measurement signal had a constant frequency of 100 Hz (lower frequencies could be cut-off by a filter). This allows the material to work as an actuator and a sensor simultaneously. Such a self-sensing element enables the integration of an actuator and a feedback loop in one element. Danfoss designed an energy storage device based on DE. Charging a stretched polymer and relaxing it afterwards leaves some charge inside it. This energy can be stored by the element and harvested later (fig. 2). This opens various application possibilities, such as scavenging energy from the environment – this energy can be later used to power the own actuation of the element, charge batteries or power electronic devices.

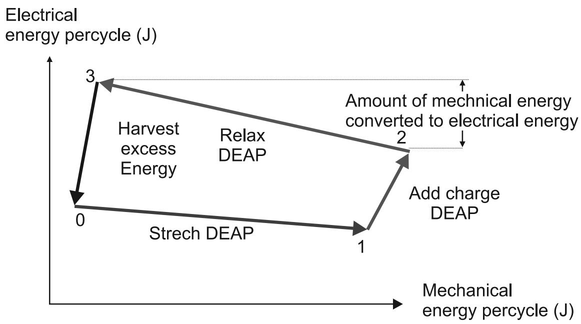


Fig. 2. Energy harvesting cycle of a dielectric elastomer [9], DEAP – dielectric electroactive polymer
Rys. 2. Cykl odzyskiwania energii elastomeru dielektrycznego [9], DEAP – elektroaktywny polimer dielektryczny

## 2.2. Types of actuators

An electroded dielectric film can be manufactured in large variety of shapes: stretched over a rigid frame, rolled into a scroll, formed into a tubular shape, or laminated on a flexible substrate to form unimorphs and bimorphs [10]. Each of these shapes offer different actuating possibilities, i.e. large displacement with smaller force or large force with smaller displacement. Solutions already invented to work with piezoelectric actuators can be used with DE as well.

In this paper, applications of stack actuators are presented. Stack actuators (a solution used in piezoelectric actuators) consist of several layers of dielectric elastomer, alternated by layers of conducting electrodes. It offers large linear displacements and forces, but is difficult to manufacture. Applied electrostatic field is perpendicular to the electrodes and dielectric film. Electrically it is a number of capacitors connected in parallel with opposite polarization of each layer. A more complex actuator, designed by Carpi et al. [11] consists of a two helical compliant electrodes with an elastomeric insulator interposed between. It offers better performance, but is even more difficult to fabricate. To overcome these difficulties, a folded actuator has been designed.

Dielectric polymers were used in primary research by the authors of the project. The aim of the investigation was to build a simple set to experiment on one-layer EAP actuator. An acrylic elastomer tape (VHB 4910) and graphite dust were used to build the actuator. The tape, manufactured by 3M is a very strong joining material (commonly used in construction). Such tapes exhibit the best strain, stress and energy density characteristics. Because of high elasticity it can be easily stretched in any planar direction.

In the first stage of the studies (similarly to Kofod experiment [6]) the tape was stretched 500% along the x axis, and then attached to plastic beams (Fig. 4). Then, the tapes with five different pre-stretches (100%, 200%, 300%, 400%, 500%) were examined. When 5 kV voltage was applied, a change in the thickness and corresponding change in the area of the electrodes were observed. A prototype of a stack actuator was created by the authors.

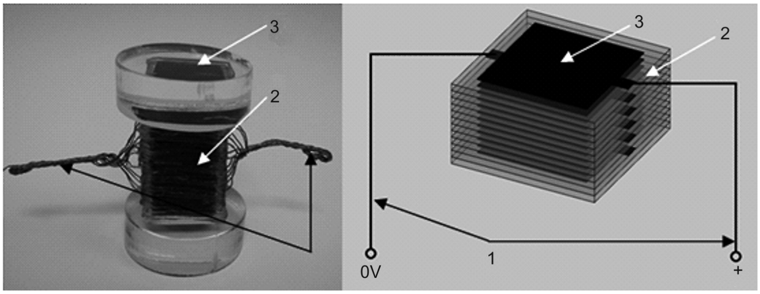


Fig. 3. Prototype of a stack actuator: 1 – electrical wiring, 2 – elastomer tape, 3 – graphite electrode

Rys. 3. Prototyp aktuatora warstwowego: 1 – druty elektryczne, 2 – taśma elastomeru, 3 – grafitowe elektrody

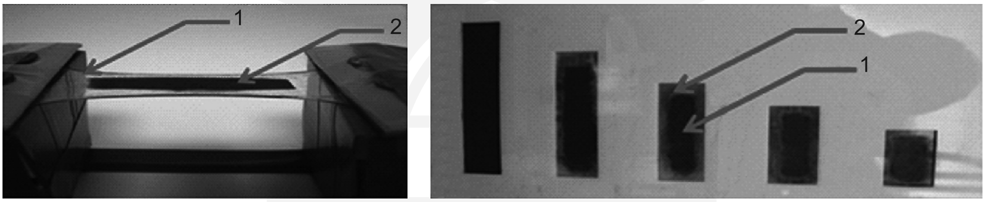


Fig. 4. Author's experiment: a single layer of pre-streched dielectric film VHB 4910 covered with graphite electrode. 1 – dielectric elastomer, 2 – graphite electrode

Rys. 4. Eksperyment Autorów: pojedyncza warstwa rozciągniętej taśmy VHB 4910 pokrytej grafitową elektrodą: 1 – dielektryczny elastomer, 2 – grafitowa elektroda

## 3. Applications of dielectric elastomers

A variety of technical applications of dielectric elastomers are discussed in literature. These smart polymers can be applied in biomedical sciences, robotics, mechatronics, entertainment, military, aeronautics etc. Two applications of dielectric elastomer actuators are presented in this paper as a kind of prosthesis – an active orthosis and a force feedback device. Both devices exert force on user's hand, thus the safety of the user has to be strictly considered. Dielectric elastomers can be easily used in both cases. A DE actuator is physically unable to exceed a safe value of force, also inactive actuator can still be moved freely. The only risk is associated with high actuating voltage (currently approximately 5 kV), but with carefully following safety norms, the user will be completely separated from such elements.

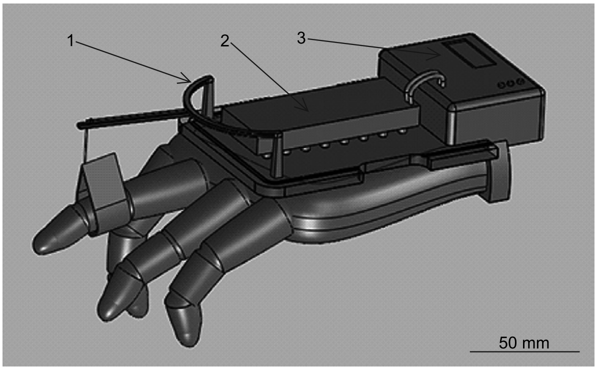


Fig. 5. CAD model of an active orthosis: 1 – interchangeable mounting element, 2 – dielectric elastomer actuator, 3 – control box

Rys. 5. Model CAD aktywnej ortezy: 1 – wewnętrzny element montażowy, 2 – aktuator z elastomeru dielektrycznego, 3 – skrzynka kontrolna

### 3.1. Orthosis

Orthoses are devices that accelerate the rehabilitation of damaged joints. Static and passive orthoses are most popular, but more serious injuries require active elements. These elements move the healing joint with low speeds and controllable force to prevent scarring and inflammations, while not causing pain. Currently such devices are driven by hydraulic, pneumatic of electrical actuators. All these solutions have serious disadvantages, such as complicated way of supplying power, high mass or generated noise. Dielectric elastomer actuators are lightweight, silent and do not require complicated mechanical elements such as gearboxes. High actuating voltages can be supplied by miniature DC-DC converters, enclosed in a control box (Fig. 5).

Presented solution is designed for a smaller DE actuator (Figure 5) – a lower force will be generated. It is also equipped with interchangeable mounting element (Fig. 5). This allows the device to be used with different fingers and joints, for a variety of finger lengths (e. g. for children). The force can be applied with various angles.

### 3.2. Force feedback device

A force feedback device is used in the manipulation of objects in a virtual reality. It usually is used as an input/output device connected to a PC. A glove with actuators is worn by a user. Whenever a virtual object is touched or grasped, the actuators do not allow a user's fingers to move further. Ideally, such a device could inform the user not only about the existence of an object, but also about its surface, shape, plasticity or temperature.

Minimum force variation that can be detected by a human's fingertip is 0.5 N, so the smallest controllable change in the generated force cannot be higher. Maximum force is restricted by user's safety – in most cases it should not exceed 30–50 N [12]. Minimum displacement registered is 2.5° angular displacement of the joint, which is approx. 1 mm of fingertip linear displacement. The sensitivity of the motion of a force feedback device should be at least four times higher – 0.25 mm (fingertip) or 0.6° (joint). Maximum displacement varies with the size of human hands – devices with different sizes seem to be sensible. The mass of the device should be as low as possible to give a natural feeling of operation. For the same reason, the actuator should not generate force while not operating. The high power density of dielectric elastomers lowers the mass significantly. Inactive DE actuator has a 'natural feel' while handling it, and a force opposite to finger's movement can be generated to ensure the feeling of free movement. Self-sensing capabilities of dielectric elastomers can eliminate the need of using separate sensors, creating a compact and simple device.

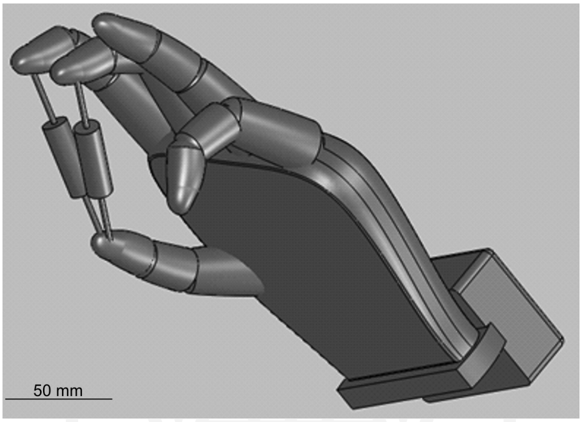


Fig. 6. Designed force feedback device

Rys. 6. Urządzenie do siłowego sprzężenia zwrotnego

Future developments could be equipped with tactile displays, which inform the user of the surface of a virtual object. Development of electroactive polymer actuators could also allow an FFD to look like a glove, with the actuators embedded in its surface.

## 4. Conclusions

Dielectric elastomers can be easily applied in many areas of science. Perfecting the production technology will enable the devices built with such actuators to be manufactured on large scale and compete with existing solutions. The study showed that in the area of prosthesis such as active ortheses, a DE actuator would make the devices more patient-friendly and universal. As far as force feedback devices are concerned, the presented design is much simpler than existing devices. Using polymeric materials also shows very interesting prospects for the future.

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