Actuator Based on a Dielectric Elastomer with Quartz as a Filler for Vacuum Technology

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Abstract. Modern equipment requires precise movement of objects both at atmospheric pressure and in vacuum conditions. Moreover, vacuum equipment is subjected to a number of external disturbances that adversely affect the manufacturing process and have a direct impact on the quality of manufactured products. A promising development in this area is actuators based on dielectric elastomers, characterized by a short reaction time (milliseconds) and a simple and cheap implementation. Successful implementation depends on an understanding of its behavior and properties, depending on the choice of matrix and filler materials. Most often, expensive barium titanate is used as a filler. This paper discusses the use of quartz as a cheaper filler.

1. Introduction

Modern mechanical-engineering equipment increasingly requires precise movement of objects both at atmospheric pressure and in vacuum conditions. To ensure accurate movement and vibration isolation of objects, mechanisms of precise movements (actuators) based on "smart" materials and, in particular, controllable magneto- and electroactive materials, liquids and polymers, have become widespread [1].

Polymers that exhibit a change in shape or volume when stimulated by an electric voltage or current are called electroactive polymers, or EAPs. These active substances can be classified in accordance with their principle of operation [2, 3] as ionic and electronic ones. Ionic EAPs: the movement of ions during electrical activation is responsible for a change in shape or volume. Ions controlled by an external electric field, as a rule, diffuse through a liquid or solid electrolyte and, thus, cause an electromechanical change in the material configuration. Electronic EAPs: electric charges are displaced upon activation of electronic EAPs. The resulting electrostatic forces lead to electromechanical changes in the shape or volume of the material [4].

Dielectric elastomers (DEs) are one of the most promising representatives of electronic electroactive polymers, since they can provide large deformations and withstand high loads. The properties of this material, enclosed between the electrodes, are controlled by an external electric field: an electric voltage of several kilovolts is applied to two conductive electrodes, and the dielectric layer is compressed as differently polarized electrodes are attracted to each other. In addition, electrostriction occurring in a dielectric medium contributes to the general deformation of DE [5].

2. Main components of DE

The main components of DE are: elastomeric matrix and a dielectric powder filler. When choosing the material of the DE matrix, it is important to consider the following requirements: high dielectric constant, a wide range of operating temperatures, high electric strength, low Young’s modulus; therefore, synthetic or natural rubbers are
used as the DE matrix, and the matrix can also be made by mixing one, two or more materials. The mixing of several materials as components of the matrix is made in order to improve its characteristics, but often the enhancement of one parameter leads to a deterioration of other characteristics of the material [6, 7].

The DEs with matrices based on three types of polymers: silicone, acrylic and polyurethane, are considered most promising today, but other materials, for example, natural rubber, are practically not investigated due to lower values of required characteristics [8].

| Matrix material | Young's modulus, MPa | Dielectric constant | Electric strength, kV/mm | Temperature range |
|-----------------|----------------------|---------------------|--------------------------|------------------|
| Silicone        | 0.1...10             | 2...5               | 50...350                 | -100...200°C     |
| Acrylic         | 0.6                  | 4...6               | 45...250                 | -10...80°C       |
| Polypropylene   | 17                   | 6...7               | 160                      | -              |

The DE can be improved by adding fillers to the elastomer matrix; their dielectric properties are high and can enhance the dielectric properties of elastomers several times. Therefore, finely dispersed barium titanate powder, which may have a relative dielectric constant of up to 3000, is most often used as a filler [9].

The manufacturing of a highly dielectric and finely dispersed powder of barium titanate is a time-consuming and expensive operation, so the goal of the work was to test a sample in which a cheaper and more available dielectric, quartz, was used as a filler.

Mixing the matrix material and the filler material in the correct proportions is of no small importance for the properties. When mixing, a strong correlation between the dielectric constant and electric strength should be taken into account: an increase in dielectric constant is usually accompanied by a decrease in electric strength [10].

The choice of material for the electrodes is the main problem associated with the manufacturing of actuators based on DE. This is due to the fact that they must not only withstand high electric fields (up to hundreds of kV/mm), but they must also be well compatible and maintain good electrical contact during deformation. The most obvious version of the electrodes – two metal plates, is possible, but their huge disadvantage is the high rigidity of such electrodes, which usually limits the maximum achievable deformation value [11, 12, 13].

3. Manufacturing of quartz-based DE

Based on an analysis of [5, 6, 7, 8, 9, 11], in which studies of the influence of DE components’ materials on its properties are presented, silicone compound was used as a matrix for the manufacturing of prototypes, since it has the best set of properties: high dielectric strength (27 kV/mm), high elastic modulus (10 MPa) and a wide range of operating temperatures (from -60 to 200°C), as well as elongation at break up to 165% [13].

As a filler, quartz powder with a fineness of 0.5 μm was used. To study the effect of the filler concentration in the matrix volume on the DE properties, samples were prepared with a ratio of the matrix material to the filler material of 1:2, 1:4.

The manufacturing process was performed at the MT11 subdepartment of BMSTU. At the first stage, the surface of the quartz particles was covered with an active layer of polymethylsiloxane to prevent the appearance of particle agglomerates in the polymer. The obtained powder is added to the silicone compound pre-mixed with the hardener. After fifteen minutes of mixing, the suspension was placed for 20 minutes in a desiccator, which provides a pressure of 10^5 Pa using a rotary vane pump, in order to degas the polymer volume and prevent the porosity of the final product. After degassing, the polymer composition was cast into a mold providing a height of 1 mm, previously coated with a surfactant layer, and placed into a drying cabinet at a temperature of 150°C for 60 minutes. The polymerization occurred due to the chemical reaction of the vinyl group compound in the composition of silicone rubber and the hydride group in the composition of the polymerizer. After cooling the obtained polymer, samples of 40 mm in diameter were knocked out using a metal pointed form [14, 15, 16].

4. Design of quartz-based DE

The main criterion for choosing the design of DE is the direction of action. The DE is characterized by two directions of deformation: longitudinal – parallel to the field (change in thickness) and transverse – orthogonal to the field (change in surface area). The operating principle is the material volume constancy: uniaxial pressure load is equal to the biaxial tension load in the remaining spatial directions [16].
The classic version of DE for use in the actuator is a "capacitor" design. The "capacitor" design (Fig. 1) is identical to the design of a plane capacitor, but with a DE clamped between a pair of electrodes. A wide range of matrix, filler and electrode materials is suitable for this design [17].

![Figure 1. Actuator design according to the "capacitor" scheme](image1)

The multilayer structure (Fig. 2), in turn, consists of actuators of the "capacitor" design connected in series. The number of layers installed affects the linear size of the actuator and, therefore, the absolute stroke when moving [17, 18].

![Figure 2. Multilayer actuator design](image2)

Any DE materials can also be used, but it is recommended that the electrodes be made in the form of flexible thin metal ones, since electrodes based on carbon lubrication can lead to the displacement of the layers relative to each other. Therefore, electrodes were made from rolled copper sheets using laser cutting in the form of two ribbons with round segments [19, 20].

The assembly of a multilayer DE with this electrode design was performed by sequentially bending electrode segments in perpendicular planes [21].

8 DE samples were made: one-, two-, four- and eight-layer with 60% and 80% quartz concentrations.

5. DE-based precise movement mechanism

Precise movement mechanisms are characterized by such indicators as the movement error and range, load capacity, the number of degrees of freedom and the response time, and requirements for these indicators increase over time [22].

When developing the experimental design of the actuator based on DE, it is necessary to take into account the following factors: the design should be universal and suitable for using both a single-layer and multi-layer elastomer with a different number of layers, it should be made of dielectric material to provide insulation for the purpose of protection against high voltages, it should have high rigidity, backlashes should be excluded and ease of manufacture should be provided [25].

The design of precise movement mechanism presented in Fig. 3 was developed based on these requirements.
1 - top flange; 2 - rod; 3 - housing; 4 - bottom flange; 5 - disk; 6 - DE

Figure 3. The design of DE-based precise movement mechanism

The DE 6 is attached on the bottom flange, which is a fixed base 4, the rod 2 is mounted on top. The housing 3 is mounted from the top so that the contact pads of the electrodes extend through the grooves for passing the wires out. After aligning all the holes, the housing is attached to a fixed base using a screw connection. The top flange is attached to the rod 2. The assembly is mounted onto disk 5 with a screw connection. Also, there are holes on disk 5 for mounting the mechanism. A movable object is mounted on the top flange 1.

The screw connection of the movable base allows to disassemble the design and replace the DE samples without deforming either the electrodes or the entire elastomer as a whole.

The resulting design can be used for dielectric elastomers with a diameter of not more than 40 mm and a height of not more than 30 mm. The diameter value is determined by the groove in the bottom flange for positioning the DE, and the height should not exceed 75% of the housing height to avoid tilting the movable base.

6. Methods
The goal of the work was to study the properties of DE with quartz as a filler, varying the following parameters: voltage (from 0 to 2000 V), filler concentration (60% and 80%), the number of DE layers (1, 2, 4, 8). The output parameter in this case was the movement of the top base of the actuator.

To carry out the study, an experimental set-up was developed and assembled (Fig. 4), consisting of a power supply unit 1 and a high-voltage power supply unit 2, due to which the necessary potential difference is supplied to the electrodes. The voltage divider 4 allows monitoring the voltage supplied to the actuator electrodes on the voltmeter 3. Inductive sensor 5 shows the movement of the actuator top base, displayed on the control unit of the sensor 7, where one can select the desired measuring range of the sensor. Data from the sensor control unit is sent to the PC screen using ADC 8 and LabView 9 software.

Figure 4. Experimental set-up.

The experiment was carried out according to the following procedure:

1. Setting the required measuring range on the inductive sensor control unit.
2. Setting the required control voltage on the laboratory power supply.
3. Taking the control readings of the output signal of a high-voltage power supply from a multimeter.
4. Recording the value of the current sensor position for 30 seconds, converted using the ADC and the LabView program.

7. Results
During the experiment, voltage was applied to the electrodes in the range from 0 to 2000 V. A series of parallel observations of 150 pieces was taken by an inductive position sensor. Based on the data obtained during the experiment, graphs of the average movement value were plotted depending on the voltage applied to the actuator electrodes, taking into account the number of DE layers (Fig. 5, 6).
When studying the characteristics of DE with a quartz concentration in the matrix material equal to 60% (Fig. 5), the following maximum movement values were obtained: for 1 layer: -5.01 μm, for 2 layers: -19.25 μm, for 4 layers: -26.32 μm, for 8 layers: -39.81 μm. To study the effect of increasing the filler material concentration in the matrix material, samples with a quartz concentration of 80% were fabricated and studied in the actuator in the same way (Fig. 5).

An increase in the quartz concentration led to an increase in the maximum movement value by about 1.6 times: -8.08 μm, -30.55 μm, -44.12 μm, -54.86 μm for one, two, four and eight layers, respectively.

The plotted dependences prove that increasing the number of DE layers allows to increase the movement range of devices based on it, or to reduce the operating voltage required to achieve a certain movement value.

When studying the characteristics of the actuator based on similar DE samples with barium titanate – the “classical” DE filler, the following results were obtained: for one layer -15.39 μm, for two layers -35.35 μm, for four layers -39.11 μm, for eight layers -68.24 microns.

Comparison of the results obtained for DEs based on barium titanate and quartz, we can conclude that quartz can be considered a cheaper analogue of barium titanate for the manufacturing of DEs. Thus, using quartz as a filler, it is possible to achieve a 15 μm worse result on 8 DE layers, but at the same time reduce manufacturing costs by several times.

8. Conclusion
Despite the current state of traditional electronic technologies, there is increasing demand for movement mechanisms that work on new principles. This study showed that dielectric elastomers, depending on their
composition and design, can exhibit a wide range of different properties, the use of which in various fields is very promising, in particular – in creation of actuators of high accuracy and efficiency.

It was found that there is a dependence of the actuator top base movement on the number of DE layers, the filler material concentration, and the voltage at the electrodes: an increase in any of the parameters leads to an increase in the output parameter. It is established that for DE manufacturing quartz can be considered a cheaper analogue of barium titanate.

The plotted dependences prove that an increase in the number of DE layers makes it possible to increase the movement range of devices based on it, or to reduce the operating voltage necessary to achieve a certain movement value; the same can be said about increasing the concentration of filler in the matrix.

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References

[1] Samatham R, Kim K J, Dogruer D, Choi H R, Konyo M, Madden J D and Yim W 2007 Active polymers: an overview. Electroactive polym. for robotic app. (London: Springer) pp 1-36
[2] Bauer S 2014 Dielectric Elastomers. Encyclopedia of Polymeric Nanomaterials pp 1-9
[3] Bar-Cohen Y 2004 Electroactive polymer (EAP) actuators as artificial muscles: reality, potential, and challenges (Bellingham, WA: SPIE press) 136 1-765
[4] Lochmatter P 2007 Development of a shell-like electroactive polymer (EAP) actuator (ETH Zurich).
[5] Brochu P, Pei Q 2012 Dielectric Elastomers for actuators and artificial muscles. Electroactivity in Polym. Mat. (Boston, MA: Springer), pp 1-56
[6] Smela E, Inganäs O, Lundström I 1995 Controlled folding of micrometer-size structures Science 268 1735
[7] Jung M Y, Chuc N H, Kim J W, Koo I M, Jung K M, Lee Y K and Koo J C Mar. 2006 Fabrication and characterization of linear motion dielectric elastomer actuators Smart Struct. and Mat. 2006: Electroactive Polymer Actuators and Devices (EAPAD) 6168:616824 International Society for Optics and Photonics
[8] Otero T F, Angulo E, Rodriguez J and Santamaria C 1992 Electrochemomechanical properties from a bilayer: polypyrrole/non-conducting and flexible material – artificial muscle J. Electroanalyt. Chem. 341(1-2) 369-75.
[9] Wang H and Zhu J Nov. 2008 Implementation and simulation of a cone dielectric elastomer actuator Optomechatronic Tech. 2008 7266:726607 International Society for Optics and Photonics
[10] Fink J K 2012 Polymeric sensors and actuators (John Wiley & Sons) Vol. 1
[11] Carpi F, Chiarelli P, Mazzoldi A and De Rossi D 2003 Electromechanical characterisation of dielectric elastomer planar actuators: comparative evaluation of different electrode materials and different counterloads Sens. and Act. A: Phys. 107(1) 85-95
[12] Brochu P and Pei Q 2010 Advances in dielectric elastomers for actuators and artificial muscles Macromolecular rapid comm. 31(1) 10-36
[13] Tsibizova T Y, Guzeva T A 2016 Automatic control systems for technological processes of curing products made of polymeric composites Polym. Sci. Ser. D 9(1) 22-6
[14] Oohira K 2010 U.S. Patent No. 7,678,853 (Washington, DC: U.S. Patent and Trademark Office)
[15] Al-Ibadi M 2015 Experimental study of a dielectric elastomer
[16] Rasmussen L (ed) 2012 Electroactivity in polymeric materials (Springer Science & Business Media)
[17] Behboodi A and Lee S C K June 2019 Benchmarking of a Commercially Available Stacked Dielectric Elastomer as an Alternative Actuator for Rehabilitation Robotic Exoskeletons Proc. 2019 IEEE 16th Int. Conf. on Rehabilitation Robotics (ICORR) pp 499-505
[18] Ma W and Cross L E 2004 An experimental investigation of electromechanical response in a dielectric acrylic elastomer Appl. Phys. A 78(8) 1201-4
[19] Rosset S, Niklaus M, Dubois P and Shea H R 2008 Mechanical characterization of a dielectric elastomer microactuator with ion-implanted electrodes Sens. and Actuators A: Phys. 144(1) 185-93
[20] Pagano C, Malosio M and Fassi I Feb. 2010 Monodirectional Positioning Using Dielectric Elastomers Intl. Precision Assembly Seminar (Berlin, Heidelberg: Springer) pp. 180-7
[21] Prahlad H, Pelrine R, Kornbluh R, von Guggenberg P, Chhokar S, Eckerle J and Bonwit, N May 2005 Programmable surface deformation: thickness-mode electroactive polymer actuators and their applications *Smart Struct. and Mat. 2005: Electroactive Polymer Actuators and Devices (EAPAD)* 5759 pp 102-13 International Society for Optics and Photonics

[22] Zarubin V S, Zimin V N and Kuvyrkin G N 2019 Temperature State of a Hollow Cylinder Made of a Polymer Dielectric with Temperature-Dependent Characteristics *J. Appl. Mech. and Tech. Phys. 60*(1) 59-67

[23] Yoo I S, Reitelshöfer S, Landgraf M and Franke J 2015 Artificial Muscles, Made of Dielectric Elastomer Actuators-A Promising Solution for Inherently Compliant Future Robots *Soft Robotics* (Berlin, Heidelberg: Springer) pp 33-41

[24] Laryushkin P A, Erastova K G, Filippov G S and Kheylo S V 2019 Calculation of Delta-Type Mechanisms with Linear Actuators and Different Numbers of Degrees of Freedom *J. Mach. Manuf. and Rel. 48*(3) 204-10

[25] Mikhailov V P, Bazinenkov A M, Dolinin, P A and Stepanov G V 2018 Dynamic Modeling of an Active Damper *Rus. Eng. Research 38*(6) 434-7