# Development and Research of Electro-and Magnetocontrollable Elastic Polymeric Materials for Soft Robotics

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*Abstract*—**New silicone magnetoactive elastomers have been investigated. Changes in elastic properties and resonance frequencies shifts in the investigated composite materials samples at the imposition external constant magnetic fields have been fixed by dynamic testing methods on vibration test benches. The method is developed and a calculation example necessary deformation creation in a magnetoactive material by means of electromagnetic fields influence is shown. The given technique of using the influence on the polymer elastic material by the electromagnetic field creates the possibility, by means of the given program specifications, to support the necessary decision on changing the dynamic characteristics (in accordance with the task changing factors in view). The material under development has a direct relation to robotics sensation, to creation of materials which are also called "smart materials". The studies show their possible application as intelligent sensors or sensors with magnetic field force feedback, which transmit signals to the computer's software control unit to support optimal decisions for "soft robotics" specified by the technical conditions. The material can be adapted as a touch sensor, allowing robots to feel the change in elastic properties in the object being contacted. The results show that it is possible to create structures for use in robotic devices based on electrically and magnetically controlled elastic polymer materials, providing a number of advantages over those currently in use.**

*Keywords*—*magnetoactive silicone composites, dynamic tests, deformations, materials of soft robotics*

## I. INTRODUCTION

In modern robotics industry, materials are developed with a set of fundamentally new properties that could be controlled by external influences [1]. Soft robotics: a new relatively recently emerged direction in the multilateral field of creating robotic systems. An interest in the creation and development of flexible devices for soft robotics lies in the possibility wide use as actuators that are adjustable in elasticity and strength, for example, grips in the robotic device designs. Prospects for the soft robotics development are associated with research in the field of creating an elastically deformable organic material that simulates the muscles work. The main task in creating the mechanism of modeling and reproducing movement similar to muscle contractions is the innovative polymer composite materials development. Composite materials consisting of rather rigid polymer matrices filled

with magnetic particles have been known for a long time [2]. Traditional magnetic elastomers have low flexibility and practically do not change their size, shape, or elastic properties in the external magnetic field presence. Magnetorheological composites, that is, materials whose rheological and mechanical properties change dramatically under the external magnetic field influence, attract great attention [3–5]. They consist of a non-magnetic carrier – a medium in which magnetic particles stabilized against aggregation are dispersed. The filler particles structuring under the action of an external magnetic field also takes place in magnetorheological elastomers (MRE), which can be considered as solid analogs of magnetorheological fluid (MRF) [6–7]. In MRE, particles are included in the polymer matrix and cannot move freely. However, if the matrix is sufficiently soft, then the particles can move from their initial positions under the applied magnetic field action. A significant advantage of MRE over MRF is the long-term operation stability, since magnetic particles in the MRE lack sedimentation. The resulting composite structure is determined by the balance between magnetic and elastic forces. This leads to the remarkable numerous effects observed in such magnetoactive composites. In addition to the magnetorheological effect, a magnetoelectro-rheological effect is observed — a change in the composite viscoelastic properties under the simultaneous external magnetic and electric fields action that occurs when electroactive polymers are added to the material [8]. Significant magneto-deformation and magnetostrictive phenomena have been established — MRE deformations in external inhomogeneous magnetic fields [9–11]. Magnetic shape memory phenomena have been discovered — the ability to change shape in a magnetic field under an external load and maintain it until the magnetic field is turned off [10-12]. Magnetoresistive, piezoresistive, and magneto-piezoresistive properties were determined — a change in electrical conductivity under the magnetic field influence, external mechanical deformation, and under the influence of mechanical pressure and magnetic field [13–16]. Magnetodielectric, magnetooptical, and magnetoacoustic effects were revealed — changes in the dielectric permittivity, transparency, and sound wave propagation velocity in MRE composites induced by external magnetic fields, respectively [17-19]. The MRE surface

properties are studied using atomic force microscopy [20]. Using the dependence of these elastic, rheological, electrical and other MRE properties on the external magnetic field, magnetic and electric field sensors, controlled damping devices, and engineering products shock absorbers are created [21-23]. However, many problems remain in the new generations effective MRE materials creation. The study of changes in the internal microstructure magnetically active composites occurring under such external influences is the utmost interest. In the joint studies of Institute of Applied Mechanics, Mechanical Engineering Research Institute of the Russian Academy Sciences and State Scientific Center State Research Institute for Chemical Technologies of Organoelement Compounds with the atomic force microscopy help, the magnetic filler restructuring that occurs in such composites under the external magnetic field influence was directly visualized. Further research was carried out on the surface structure of a similar magnetoactive composite using scanning electron microscopy (SEM) and atomic force microscopy (AFM) [24-25]. The results obtained make it possible to better understand the observed unique effects characteristic for such magnetoactive elastomers.

## II. EXPERIMENTAL STUDIES

In the test sample, carbonyl iron powder with an average size about 5 μm is used as the magnetic filler of the silicone polymer matrix. The concentration of magnetic filler in the composition is 75% mass. Modified magnetic fillers powders are mixed with SIEL liquid silicone compound (manufactured by the State Scientific Center State Research Institute for Chemical Technologies of Organoelement Compounds) at a temperature 150 degrees for the polymerization process. During the polymerization process, three-dimensional crosslinking of two oligomers containing vinyl and hydride groups occurs. The resulting materials have high elasticity and heat resistance up to 200°C.

The different dynamic test series on a cylindrical sample 3 cm long and 2.8 cm in diameter are carried out.

In one test series, the sample is rigidly fixed on the vibrator table of the vibration test complex. It is shown in Fig.1. Various oscillations frequency ranges are set from 20 to 300 Hz (Hertz), and magnetic fields acting on the sample were used; the attractive force on the sample created by the magnetic field was 14.5 N (Newtons). It was found that exposure the sample with different strength magnetic fields led to a resonance frequencies shift to the high-frequency region by almost a factor of two (the resonance frequencies arrangement shifted from 85 Hz to 170 Hz) [23,26]. Based on the results obtained, a damper device was developed [27]. In these tests, the detuning or removal from resonant frequencies is performed using the magnetic interaction forces with carbonyl iron particles. The use of fillers with a stronger dipole-dipole interaction will expand the boundaries of the detuning from resonant frequencies.

The developed device is a feedback system that allows constantly monitoring the working object maximum permissible vibration operation modes and configuring the system in automatic mode for the lowest possible vibrations.

This development can be used, for example, with active, controlled damping of oscillations and vibrations in various machines. The use of variable stiffness controlled, elastic elastomers as grippers is also possible in robotics. It is also possible to use them in the medical industry for prosthetics. The studied "smart materials" – magnetically and electroactive polyurethanes and elastomers can find applications in defense and space products.



Fig. 1. Test sample with sensors on the vibrator table.

In another test series, an elastomer sample is suspended on threads. Small-sized sensors, piezo-accelerometers and a microelectric motor, which creates the test sample dynamic deformations, are fixed at both sample ends. Shown in Fig.2. The sample is exposed to unbalanced forces transmitted from the imbalance on the rotor of the electric motor rotating at different speeds. The rotor speed of the engine rises smoothly to several thousand revolutions per minute. Loads are created by a harmonic force forming a longitudinal wave of oscillations at the input of the sample.



Fig.2. Above: test specimen under the deformations nfluence; below: control unit

Fig.3 shows the sample equipment and the vibration oscillograms recording on a digital oscilloscope under the

influence a vibrating rotor of an electric motor and a magnetic field with an induction 1.2 T (Tesla). Under the influence unbalanced forces of imbalance generated on the rotating rotor outer diameter, transmitted strains oscillograms are recorded at the test sample input and output, depending on the change in the rotation speed unbalanced rotor of the electric motor.



Fig.3. Recording oscillograms of deformations transmitted through the test sample.
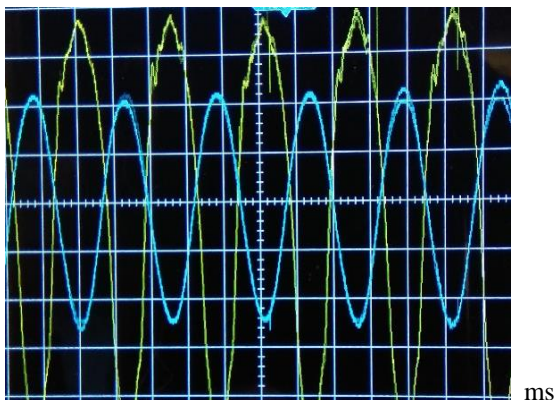
A



ms

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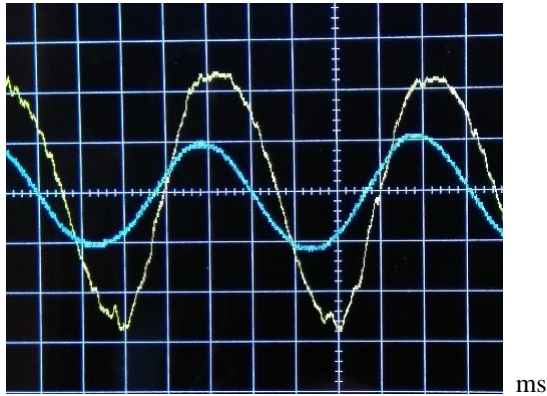
Fig.4. Oscillograms under the magnetic fields influence at various engine speeds.

The oscillograms shown in Fig. 4 along the vertical axis - A show millivolts; one division corresponded to 200 mV; on

the horizontal axis, time in milliseconds – ms; one division corresponded to 2 ms (1 mV corresponded to 7.4 m/s$^2$ ). The input signals on all oscillograms are shown in a lighter, yellow color (tone) and have acceleration amplitude larger values compared to output signals having acceleration amplitudes lower values shown in blue. The sample suspension shown in Fig.3 for conducting dynamic tests allows waves that arise under the action of a sinusoidal load to move freely or propagate from one end of the sample to the other end. A smooth signal phase shift at the output relative to the signal phase at the input was observed with increasing engine speed. It was found that the force field created by the magnet used can affect the test sample and reduce the oscillation amplitudes at the sample output in certain ranges of engine rotation speeds.

## III. CONDITIONS FOR CREATING MOVEMENTS IN AN ELASTIC POLYMER MATERIAL

For modeling the magnetoactive polymeric materials motion possibility, it is necessary to overcome the arising elastic forces, the material sample static and dynamic deformation $\Delta l$ . The condition must be met:

the magnetic force of a magnet or an electromagnet acting on the test sample $F_{el}(Fm)$ was equal to or greater than the elastic force $Fr$ (the polymeric material internal molecular forces that prevent the sample deformation). The magnetic force calculation of an electromagnet is given in [28]. In the case we are considering, the condition must be met:

$$F_{el}(Fm) \geq Fr \rightarrow \frac{B^2}{2 \cdot \mu \cdot \mu_0} = E \cdot \frac{\Delta l}{l_0}.$$ Here $B = \mu \cdot \mu_0 \cdot H =$

$$\mu \cdot \mu_0 \cdot w \cdot I \rightarrow w^2 \cdot I^2 = \frac{2 \cdot E \cdot \Delta l}{\mu^2 \cdot \mu_0 \cdot l_0}.$$ Here $B$ – magnetic

field induction, $H$ –magnetic field strength, $\mu$ – ferromagnet magnetic permeability, $\mu_0$ – air (vacuum) magnetic permeability, $w$ – winding turns number, $I$ – current strength, $E$ – elastic modulus of the material, $l_0$ – the sample initial length. Substitute the values in the resulting formula: $E = 5 \cdot 10^6$ (Pa). Set $\Delta l = 10^{-3}$ (m), $l_0 = 30 \cdot 10^{-3}$ (m). Get $w^2 \cdot I^2$

$$= \frac{30 \cdot 10^6}{12,56} = 2,39 \cdot 10^6 \text{ or } w \cdot I = \sqrt{2,39 \cdot 10^6} \cong 1,55 \cdot 10^3 = 1550.$$

Thus, for a given current strength $I$ = 1 (A) we have the turns number $w = 1550$. The coil cross section of the solenoid (electromagnet) is also calculated by the well-known formula: $R_{sol} = \rho_{cop} \cdot l_{wir} / d_{wir}$ . For the given lengths and diameters, $R_{sol} = 0,2$ ($mm^2$ ). Where: $l_{wir}$ ($m$) – the full length coil wire $n$ turns of the solenoid (electromagnet); $\rho_{cop}$ ($\Omega \cdot m / mm^2$ ) – the copper wire resistivity; $d_{wir}$ ($mm$) – a copper wire section. Consider the sample vibrational (dynamic) deformation. It is commonly known that, the electromagnet static lifting force occurs when a direct current $I$ flows through its winding, and a constant magnetic

induction $B = \mu \cdot \mu_0 \cdot I$ occurs between the electromagnet poles. If a variable electromotive force $u = U \cdot Sin\omega \cdot t$ is connected to the electromagnet ends, then alternating current $i = I \cdot Sin\omega \cdot t$ will flow through the electromagnet winding, where, frequency $\omega = 2 \cdot \pi \cdot f$, $f$ – in Hz, while $f = \dfrac{1}{T}$, $T$ – the time in seconds. The desired electromagnet lifting force $fel$ must overcome the elastic forces $fr$, i.e. the lifting force must be greater than or equal to the material elastic force. Under this condition, it is allowed to equate these forces in order to calculate the system parameters providing a given deformation: $fel = fr$. As a result, we get: $2 \cdot \pi \cdot 10^{-7} \cdot \mu^2 \cdot n^2 \cdot I^2 m = \dfrac{E}{l_0} \cdot \Delta l$. After substituting the given values, we get $n \cdot I m = 257.58 \, (A \cdot turns) \approx 300 \, (A \cdot turns)$. At $I m = 1(A)$ the number of turns will be $n = 300$; at $Im = 0.1(A)$, respectively $n = 3000$ *turns*, for a given sample deformation 1 mm. For large values of deformations of the sample, correspondingly high currents will be required with the corresponding calculated number of turns.

The results of the considered experimental models and the calculations show the possible and achievable conditions for creating and controlling the sample movements under the electromagnetic forces action by a specified value.

## IV. Conclusion

The volumetric deformation possibility of the test material under the magnetic fields influence is substantiated.

The polymeric electro- and magnetorheological materials creation with a special structure that reacts and changes the relative mutual position of the particle components on the electro- and magnetic fields effect will allow them to create significant and controllable internal deformations with the magnetic shape memory effect.

The obtained results serve as the basis for the design of actively controlled feedback elastic polymer materials for soft robotics, as well as promising new-generation magnetostrictive engines with significant force effect micro-transmission capabilities of on controlled objects.

The experiments conducted on vibration stands showed the possibility of a resonance frequencies significant shift in such composites under the magnetic fields influence. It is planned to use these effects in creating an actively controlled feedback damper by detuning from a resonant frequency a vibrating object by changing the magnetoelastic supports elastic-stiffness characteristics. So it is possible to automatically control and maintain a technical objects minimum vibration level.

The recorded oscillograms show the characteristics of the change in the test sample deformation properties under the considered external loads actions. The input and output wave parameters dependences are established: acceleration amplitudes from the magnetic field influence on the test sample. The oscillation amplitude dependences of changes in the phase shifts at the sample output relative to the input with a change in the exposure frequency at the input are established.

The mix of combinations developed by various constituent material components will create a new class composite polymer materials with specified controlled dynamic properties.The values of the movements (deformations) created in the IEM are controlled on the basis of the technological (intellectual) decisions set by the control software in the robotic device.

Due to the high technological capabilities of using the developed and tested electro-and magnetically controlled elastic polymeric materials, it is advisable to continue research and development of elastic polymeric materials structures for soft robotics.

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