Influence of the geometry on magnetic interactions in a retina fixator based on a magnetoactive elastomer seal

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Abstract. We study the effects the geometric configuration has on magnetic interactions between a magnetoactive elastomer (MAE) sample and various systems of permanent magnets for problems with both flat and curved geometry. MAEs consist of a silicone polymer matrix and iron filler microparticles embedded in it. Permanent magnets are cylindrical neodymium magnets arranged in a line on a flat or curved solid surfaces. We use computer simulations, namely the finite element method, in order to study the interaction force and magnetic pressure in a system with an MAE sample and permanent magnets. The model is based on classical Maxwell magnetostatics and two factors taking into account field dependence of MAE’s magnetic properties and inhomogeneities caused by local demagnetization. We calculate magnetic pressure dependences on various geometric parameters of the system, namely, the diameter and the height of permanent magnets, the distance between the magnets and dimensions of MAE samples. This research aims to create a set of guidelines for choosing the geometric configuration of a retina fixator based on MAE seals to be used in eye surgery for retinal detachment treatment.

1. Introduction

Magnetoactive elastomers (MAEs) are polymer composite materials that have magnetically sensitive filler particles embedded in the polymer matrix [1-13]. The main property that characterizes these smart materials is their high responsiveness to external magnetic fields. Viscoelastic as well as magnetic properties of MAEs can be controlled externally [1-5]. The most widely used components of the composite are silicone-based soft matrices and micron-sized iron particles [3,4].

Magnetorheological effect, i.e. the changes to viscoelastic properties that occur in an MAE sample under the influence of external magnetic fields [1-5], and magnetodeformational effect, i.e. spontaneous deformation in magnetic field [6-11], serve as a basis for using MAEs as elements of tunable damping devices [12] and cell substrates [13]. This paper is dedicated to studying the MAEs for medical purposes, namely a surgical treatment of complicated retinal detachment cases [14-16]. It is proposed to seal the retinal break with an MAE while a system of permanent magnets placed outside of the eye provides the necessary magnetic field to turn the sample into a proper mechanical fixator. The MAE attracts to the system of magnets and also changes its properties to match the needs of the task at hand. The advantages of such approach include the flexibility of the material, ease of manufacturing and the lack of any eye trauma. The magnetic buckle consisting of several magnets
covered by medical silicone rubber is sutured to the sclera, and a MAE seal is introduced into the eye through a small incision and placed on the retina surface.

This paper continues and improves upon our previous combined theoretical and experimental study demonstrating high prospects of using an MAE as an element of a magnetic fixator for treatment of complicated retinal detachments [17]. Our previous work involved setting up the model and checking its validity through calculation of the interaction parameters for test flat configurations as well as comparison with experimental data [17]. Here we are exploring how varying the geometric configuration of the system affects the results. We choose system configurations with dimensions appropriate for eye surgery applications. Furthermore, we perform calculations for curved configurations corresponding to real eye problem and reveal how the fixator curvature affects its efficiency.

This paper is organized as follows. In the next section we describe the geometry of the problem. We then recreate this geometry in a modeling environment and discuss the modeling setup. After that we point out the main ideas and expressions required to solve the problem. The results and discussion are followed by conclusions.

2. Materials and geometry

In this paper we make use of two main geometric setups: a regular plane-like setup and a curved sphere-like setup. They are schematically shown in figure 1. We use cylindrical NiFeB magnets and a cuboid patch of an MAE sample that can then be deformed. Magnets are arranged in a periodic pattern and form a buckle. The sample is placed above the magnetic system. When it is not stated otherwise, we consider magnets with the radius $R = 1.5$ mm and the height $h_m = 1$ mm. This choice of the magnet dimensions is the result of eye surgery requirements. The diameter of the non-magnetic silicone buckle that is commonly used nowadays in scleral buckling for treatment of non-complicated retinal detachments does not exceed 5 mm [18,19]. In a magnetic fixator the permanent magnets are supposed to be placed inside such a silicon buckle, i.e. their size should be smaller than the buckle diameter.

In terms of magnetic moments $M$ of the magnets, we consider two configurations: the first one corresponds to $M$ vectors being aligned parallel to each other (figure 1a), and the second one corresponds to the anti-parallel alignment (figure 1b). One could expect magnetic field gradients in the anti-parallel configuration to be higher providing thus a higher force acting between a permanent magnet buckle and a MAE sample.

![Figure 1](image)

**Figure 1.** Schematic representation of magnetic systems under study. (a) a part of a system of ten magnets with parallel alignment of their magnetic moments and a MAE sample; (b) a part of a system of ten magnets with anti-parallel alignment of their magnetic moments and a MAE sample; (c) a part of a curved configuration of 22 cylindrical magnets and a deformed MAE sample placed on a spherical surface.
As for the MAE seal, we perform calculations for the sample containing 75mass % of iron particles. MAEs of this composition were used in our previous publication [17] in order to test the theoretical model. The MAE sample is cuboid-shaped and it either covers the entire upper side of the magnetic buckle or has the size equal to two periods of it. When it is not stated otherwise, the sample has the thickness \( t = 0.2 \text{ mm} \). The MAE sample of this size is designed to allow introducing the seal into an eye through a small scission of 0.6-0.8 mm.

3. Modeling setup

In our modeling of the interactions between a system of magnets and a MAE sample we use a continuous medium approach. Both the sample and the system of magnets are characterized by their shape and sizes as well as their relative coordinates. We think of them as magnetic materials that either produce or respond to the magnetic field. To calculate the magnetic field configuration as well as the interaction force Finite Element Method (FEM) was used. Commercially available software COMSOL Multiphysics was utilized to that end. The main work area was a cube with a size enough for boundary conditions’ influence to become negligible. The sample and the system of magnets were placed according to symmetry. The \( \text{NiFeB} \) magnets were represented by cylinders with radii \( R \), height \( h_m \) and magnetization in the following form: \( \mathbf{M} = (0,0,M_{z}) \). The number of magnets in the system \( N \) and the distance between them \( d_m \) can also be controlled within the model.

We study two main geometric configurations: plane (figures 1a and 1b) and curved (figure 1c). The first one is much easier to consider, and as such most of the simulations are performed for the plane case. For this simulation the sample was considered to be a cuboid with set length \( l_e \), width \( l_t \) and thickness \( t \). The curved configuration corresponds to practical applications, that is, to both subsystems being placed along the curved surface of the human eye. For this simulation the sample is shaped by a spherical surface it is placed on and is characterized by the curvature radius \( R \), and the thickness \( t \). The minimal distance between the faces of the magnets and the sample was denoted as \( d \).

The conjugate gradient method was chosen as the main numerical algorithm for solving the magnetostatic problem. The relative tolerance was set to \( 10^{-4} \). The mesh consisted of tetrahedral elements with second order Lagrange polynomials. The maximum element size was chosen for each subdomain after performing several consecutive manual refinements of the mesh to achieve the relative deviation of less than 0.1% for the solution parameters on subsequent meshing steps. The mesh was also refined additionally between the sample and the system of magnets as well as in their close proximity to improve the accuracy.

For each configuration distributions of magnetic energy density \( W_m \), magnetic field \( \mathbf{H} \) and stress \( \mathbf{nF} \) as well as the electromagnetic force \( \mathbf{F}_{\text{em}} \) acting on the sample were calculated. Effective pressure \( P \) is obtained as total force \( \mathbf{F}_{\text{em}} \) per area \( S \) : \( P = \left| \mathbf{F}_{\text{em}} \right| / S \).

The comparison of the modeling results with the experimental data was performed in our previous work [17]. It has shown that two factors need to be considered when modeling the interaction between a MAE sample and a system of magnets. The first one is the magnetic field dependence of the MAE magnetic permeability function \( \mu(\mathbf{H}) \). It is one of the main properties of magnetoactive materials, so it is only natural to factor it in. The second one is demagnetization and form-factor [20]. It is known that the magnetic field inside a real object does not match external magnetic field even with permeability taken into account. It is because of how the shape of the object (or its boundary) affects the distribution of the field inside. It can be illustrated by considering the field boundary condition for the object in question and introducing a distribution of effective “magnetic charges” to satisfy the aforementioned boundary condition.

These two factors combined allow us to obtain the magnetization distribution inside the magnets which is not uniform and the dependence of the sample’s magnetic permeability on the magnetic field inside the sample instead of just an external magnetic field from the source. For the field dependence
itself we use the Langevin model and do not introduce magnetic hysteresis into our model, since the experimental results for our samples showed hysteresis to be insignificant. Our previous work contains a more detailed explanation of the modeling process with both factors taken into account as well as information about experimental support as it outlines the basis of this particular research [17]. Experimental data for cylindrical neodymium magnets ($R = 2$ mm and $h_m = 1$ mm) as well as MAE samples with 75 mass percentage of magnetic filler obtained in [17] was used to derive the necessary uniqueness conditions for the magnetization distribution and to calculate the parameters of the Langevin model respectively. These results could be found in our previous publication [14].

4. Magnetic field problem and force calculations
We calculate the force resulting from stress using the standard procedure [20]:

$$\mathbf{F} = \frac{1}{5} \mathbf{n} \mathbf{T}_{ext} dS$$

Here $\mathbf{n}$ is the external normal vector for the object and $\mathbf{T}_{ext}$ is the Cauchy stress tensor outside of the object. If the problem in question is purely electromagnetic, then $\mathbf{T}_{ext}$ stands for the Maxwell stress tensor in the corresponding area.

For air on the sample boundary the stress tensor is:

$$\mathbf{T}_{ext} = -p \mathbf{I} - \frac{1}{2} (\mathbf{H} \cdot \mathbf{B}) \mathbf{I} + \mathbf{H} \otimes \mathbf{B}$$

Here $p$ is pressure and $\mathbf{I}$ is an identity tensor.

The magnetic field problem is static, so we have the following field equations:

$$\begin{align*}
\nabla \times \mathbf{H} &= \mathbf{j}(r) = 0 \\
\nabla \cdot \mathbf{B} &= 0
\end{align*}$$

Magnetic field configuration strongly impacts both the pressure distribution on the sample surface and the overall interaction force. This is due to these characteristics being mainly affected by field inhomogeneities. Magnetic field structure plays an even larger role, if one considers small distances which are relevant to the practical medical applications of the present study.

5. Results and discussion
The interaction force (and the resulting mean pressure) depends on the geometric configuration of the system. Varying geometric parameters allows to find an optimal configuration as well as to study the sensitivity of the system to changes in the geometry. Figures 2-7 show dependences of the interaction force (pressure) on various geometric parameters of both the magnetic buckle and the MAE sample calculated for the flat configuration. The distance between the closest faces of the magnetic buckle and the MAE sample was fixed at 1.3 mm which roughly corresponds to the one in a real system (the thickness of the human eye sclera together with retina is approximately equal to 0.7 mm and a silicon layer on the surface of magnets in a buckle gives additional 0.6 mm of the distance).
Figure 2. Pressure dependence on the distance between the magnets for $R = 1.5$ mm and $h_m = 1$ mm. The MAE sample parameters are as follows: $l_x$ changes with $d_b$, $l_y = 3$ mm and $l_z = 0.2$ mm. The distance between the system of the magnets and the sample was kept at 1.3 mm. Line with triangle markers corresponds to the parallel magnetization alignment and line with square markers corresponds to the anti-parallel alignment.

In figure 2 we plot the pressure dependence on the distance $d_b$ between the magnets in the magnetic buckle. In these calculations, the length of the MAE sample was also increased simultaneously with increasing length of the magnetic buckle as a whole with $d_b$. In this case the interaction force, from one hand, should grow due to the larger area $S$ of the sample. However, distancing magnets from each other also makes the structure of the magnetic field more uniform, which in turn decreases the resulting force. As a result, the pressure slightly decreases with $d_b$. For anti-parallel configuration the inhomogeneity is much more prevalent, which leads to the pressure being practically constant in the range of small distances $d_b$ up to 0.5 mm. Figure 2 clearly confirms that the pressure produced by the magnetic buckle with alternating magnetization orientation is indeed higher. The pressure difference for two configurations (figures 1a and 1b) almost reaches 100%.

Figure 3. Pressure dependence on the size (radii) of the magnets for $h_m = 1$ mm and $d_b = 0.6$ mm. Sample parameters are as follows: $l_x$ and $l_y$ change with $R$ and $l_z = 0.2$ mm. The distance between the system of the magnets and the sample was kept at 1.3 mm. Line with triangle markers corresponds to the parallel magnetization alignment and line with square markers corresponds to the anti-parallel alignment.

Figure 3 shows the pressure dependence on the permanent magnet radius $R$. The corresponding graphs were obtained assuming the overall magnetic moment of each magnet to be changing slowly with its radius. The MAE sample’s width and length were increased together with $R$. One can see that
in case of small magnets, namely when the magnet radius is smaller than the distance between the magnets, the pressure produced in the anti-parallel magnetization configuration is even lower than in the co-directional magnetization system due to a small effective magnetic field in between the magnets. The pressure expectedly increases with the magnet radius for the both permanent magnet configurations and for $R$ exceeding $d_b$ it becomes higher for the anti-parallel system.

**Figure 4.** Pressure dependence on the height of the magnets for $R = 1.5$ mm and $d_b = 0.6$ mm. MAE sample parameters are as follows: $l_x = 35.4$ mm, $l_y = 3$ mm and $l_z = 0.2$ mm. The distance between the system of magnets and the sample was kept at 1.3 mm. Line with triangle markers corresponds to the parallel alignment of magnet magnetic moments and line with square markers corresponds to the anti-parallel alignment.

Increasing amount of magnetic material with a growing height of the magnets in the buckle obviously causes further increase in the pressure (see figure 4). Approximately two-fold difference in pressures for two types of magnetization orientation within the buckle is realized in the whole range of $h_m$.

**Figure 5.** Pressure dependence on the MAE sample thickness for $R = 1.5$ mm, $d_b = 0.6$ mm and $h_m = 1$ mm. Sample parameters are as follows: $l_x = 35.4$ mm and $l_y = 3$ mm. The distance between the system of magnets and the sample was kept at 1.3 mm. Line with triangle markers corresponds to the parallel alignment of magnet magnetic moments and line with square markers corresponds to the anti-parallel alignment.

Figure 5 demonstrates the pressure dependence on the thickness of the MAE sample at fixed dimensions of the magnetic buckle. A rapid increase of the pressure with $l_z$ is observed at MAE thicknesses smaller than 1 mm while at higher values a kind of a saturation takes place because the
“additions” the magnets are located further and further away from the sample, and the magnetic field decreases rapidly with distance.

The obtained results presented in figures 2-5 demonstrate that for system dimensions appropriate for eye surgery purposes and especially at small distances $d$ changing geometric parameters of the system can lead to a substantial change in interaction forces. This is the most apparent in the cases of the magnet radii (figure 3), the height (figure 4) and the sample thickness (figure 5). All the dependences are non-linear and exhibit linear-like behavior for small values of the geometric parameters. This can be explained by the field influence weakening with larger distances.

![Figure 6](image)

**Figure 6.** Pressure dependence on the curvature of the system. Parameters of the system of magnets are: $R = 1.5$ mm, $d_b = 0.4$ mm on average and $h_m = 1$ mm. Parameters of the undeformed sample: $l_x = 6.8$ mm, $l_y = 2$ mm and $l_z = 0.2$ mm. The real $l_x$ and $l_y$ change with $R_c$. The reference distance between the system of magnets and the sample $d = 0.7$ mm.

![Figure 7](image)

**Figure 7.** Pressure dependence on the distance between the sample and the system of magnets for $R = 1.5$ mm, $d_b = 0.4$ mm and $h_m = 1$ mm. The undeformed sample parameters are as follows: $l_x = 6.8$ mm, $l_y = 2$ mm and $l_z = 0.2$ mm. Line with triangle markers corresponds to the flat case and line with square markers corresponds to the curved case. The curvature radius for the curved case: $R_c = 12$ mm.

As the next step we investigate the effect of the magnetic system curvature on the magnetic interactions. In figure 6 the pressure vs the curvature radius is presented at fixed values of all other geometrical parameters of the magnetic fixator while in figure 7 dependence of the pressure on the distance between the magnetic buckle and the MAE sample is shown for the flat geometry and for the curved one with the curvature radius equal to that of a human eye.
One can see that increasing $R_c$ causes a slight increase in the pressure. For high values of $R_c$ the curvature influence on the pressure is small, but for $R_c$ around 12 mm, which corresponds to the curvature of a real human eye, the effect is more noticeable. The difference between the plane-like configuration and the sphere-like one with $R_c = 12$ mm is about 19%. For the $R_c$ of “infinity”, or the flat case, we have the pressure of roughly 1432 Pa. As such, while the flat geometry can be used to determine the tendencies and approximate results, it is imperative to study the curved geometry to obtain more accurate results for medical purposes.

The developed theoretical approach allows to calculate not only the average magnetic forces and pressure in the system but also the distribution of magnetic field within the magnetic fixator outside the permanent magnets (figure 8). One can see that the magnetic field concentrates near the magnetic buckle rapidly decreasing with the distance. It is also evident that the magnetic field inside the sample is inhomogeneous and is smaller than the outside field due to demagnetization. The structure of the field is substantially different from that of a flat case, since magnets are solid objects and can’t form a perfect curved surface.

![Figure 8. Magnetic field configuration for the curved geometry. Parameters of the system of magnets are: $R = 1.5$ mm, $d_b = 0.4$ mm on average and $h_m = 1$ mm. Parameters of the undeformed sample: $l_x = 6.8$ mm, $l_y = 2$ mm and $l_z = 0.2$ mm. The curvature radius $R_c = 12$ mm.](image)

6. Conclusions
In this work we continue studying the interaction between a system of permanent magnets and an MAE sample. This study in particular was aimed at simulating various possible geometric configurations of the system and considering the effect that changes in the geometry have on the interaction parameters. We used the finite element modeling in the commercially available software COMSOL Multiphysics to simulate two principal geometries of the problem: flat and curved cases. The flat case is used as a reference due to the ease of its analysis, and the curved case is used to study the specifics of the problem that would be present in the real scenario of medical applications of an MAE-based retina fixator.

It has been demonstrated that within the range of dimensions suitable for eye surgery applications even slight changes in geometry can strongly affect the interaction force and magnetic pressure. As such, it is important to both be precise when manufacturing the components of the retina fixator device and consult the modeling results to choose the optimal configuration for the task at hand.

The effective pressure dependences on the size of the magnets, the distance between them, their magnetic configuration, the size of the sample and the type of the system geometry have been calculated. The present results further reinforce the idea of using MAE-based retina fixators for surgical treatment of retinal detachment that we proposed in our previous work.
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