Novel magnetorheological brakes' simulation

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***Abstract* — Greater braking torque, in constrained volume and weight, is a primary challenge in magnetorheological brakes` design. This paper deals with the feasibility of increasing the overall braking torque by multiplying the number of its active surfaces. This problem was considered through electromagnetic simulation of a newly design magnetorheological brake. Simulation was carried out using commercial finite element method software - *COMSOL Multiphysics* software, AC/DC module. Materials magnetic properties, required in simulation process, were previously obtained from its manufacturer or were determined by measurements and applied to this simulation. Different number of tetrahedral elements was used for different parts of the proposed magnetorheological brake model, prioritizing regions in vicinity of magnetorheological fluid. Post processing was utilized to calculate the magnetic flux density distribution across the models' specific lines, areas and volume. The proposed magnetorheological brake design showed great potential for braking torque increase.**

Keywords — magnetorheological brake; novel design; finite element method simulation; materials; magnetic properties;

I. Introduction

Magnetorheological - MR brake is a type of electromechanical brake that consists of a stator, rotor, working fluid and one or more coils. The magnetorheological fluid - MRF, is the working fluid of the MR brake - MRB, and is contained between the stator and the rotor. When activated, by the control current, each coil generates magnetic field through MRBs' body. Affected by the magnetic field, the MRFs' viscosity changes [1, 2]. This rheological change leads to change in the braking torque value.

There are several MRB types [3]. Regardless of their construction differences, the direction of magnetic flux density is theirs common feature. The magnetic flux density direction needs to be perpendicular to MRFs` flow direction i.e. MRFs` active surface and needs to form a closed loop.

Form the magnetic and construction point of view, typical MRB is composed of MRF, as ferromagnetic working medium, nonmagnetic and magnetic materials. MRFs` magnetic properties can easily be obtained from its manufacturer. Nonmagnetic materials, such as aluminum, have known magnetic properties. On the other hand, magnetic properties of magnetic material such as construction steel, usually are not available, and need to be determined by measurements. The most important materials magnetic property, in this case, is the initial magnetization curve, which is a highly nonlinear characteristic. This materials magnetic nonlinearity was tackled with some earlier materials magnetic properties measurements [4].

The major issue with any MRB application, e.g. robotics, automotive, industry etc. is that the braking torque value is still far too small. There are several ways to improve the torque value. One of these ways is to use MRF with better yield characteristics and to reduce MRFs` gap size. Second is to increase the applied magnetic flux density acting on the MRF. The last one is to enhance the size of the MRFs` active surface area by multiplying the number of its layers.

The objective of this work is to simulate magnetic flux density distribution through several layers of a novel MRB design that features some of the above-mentioned braking torque improvement techniques. The distribution is analyzed by a commercial Finite Element Method - FEM software. Obtained values of magnetic flux density then can easily be converted into braking torque values.

II. Novel Magnetorheological Brake Design

A. *Magnetorheological brake types*

Authors of this paper have identified five major MRBs` types:

- drum,
- inverted drum,
- disc,
- T-shape rotor and
- multiple discs, Fig. 1.

There are design variations for each type. The disc brake design is the most common MRB type found in literature today, but the emphasis of this research is placed on the variant of the T-shape rotor brake.

Magnetorheological fluid data used in this magnetorheological brake simulation was provided by BASF ® Company. The authors of this paper would like to express its sincere gratitude to BASF Company especially to its project manager Dr. Christoffer Kieburg for all its support.

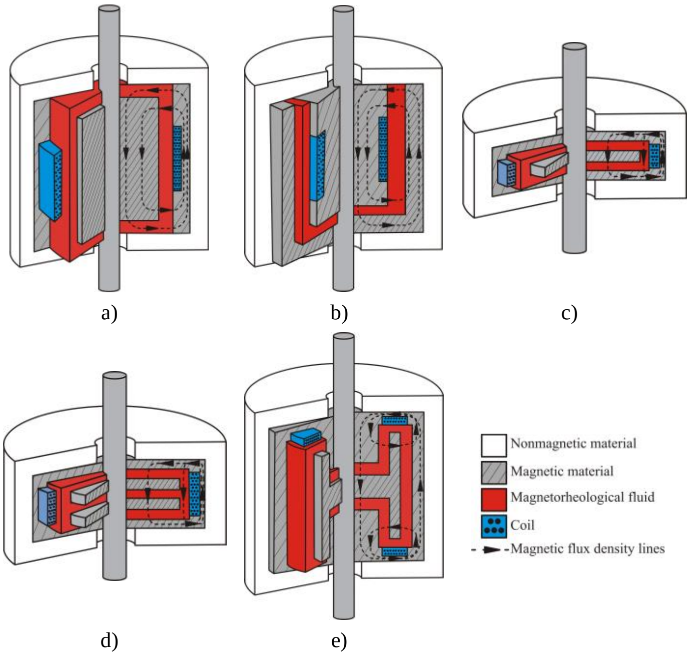


Fig. 1 Types of MR brakes, a) drum, b) inverted drum, c) disc, d) multiple discs, e) T-shaped rotor

To increase the total MRF active surfaces area, classic T-shape rotor element, Fig. 1 e) and Fig. 2 a), was concentrically multiplied four times inwards, thus forming a new multi-T-rotor element, Fig. 2 b). Proposed MRB multi-T-rotor assembly, i.e. shaft and multi-T element, is composed of both nonmagnetic and magnetic materials. In simulation, the shaft was assigned with nonmagnetic aluminum properties. Nonmagnetic shaft also features nonmagnetic disk, designated as a multi-T-element inner support, Fig. 2 b). The nonmagnetic disk diverts magnetic flux density spreading route through body of the MRB, and splits it into two magnetic flux density layers, Fig. 3 b). These two layers act uniformly onto separate but geometrically equal segments of the MRF.

The proposed MRB structure additionally has six individual stationary coils, opposed to classic T-shaped rotor brake that has two coils, thus forming a multi-pole structure. Novel design coils are radially arranged on the circumference of a MRBs' stator i.e. hexagonal prism, Fig. 3 a), b) and c). Each coils' magnetic flux density vector is directed towards the center of the MRB, Fig. 3 b) and c), thus increasing the total value of magnetic flux density acting on the MRF contained inside the brake. To have a closed magnetic circuit, there are two six-spoke magnetic flux density return bridges, Fig. 3 a) b) and c).

In the simulation, the hexagonal prism stator, the coils' cores, the multi-T-rotor element and the six-spoke magnetic flux density return bridges are assigned with magnetically soft steel C15E, [4].

The proposed MRB design torque generating capabilities can roughly be determined by the same analytical model used for the classic T-shaped rotor brake model with the results multiplication for multi-T-rotor element and MRF segments.

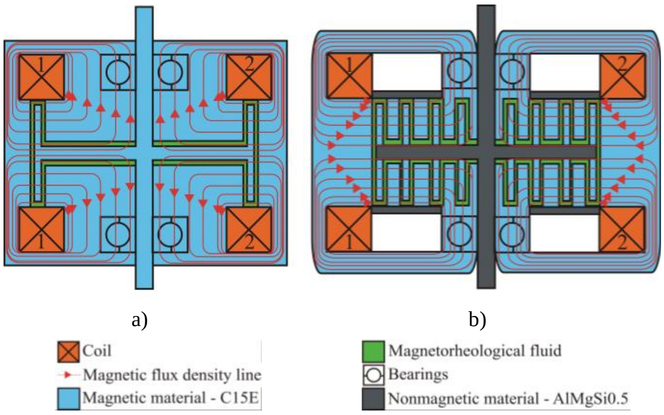


Fig. 2 Magnetorheological brakes cross sectional ilustrations, a) classic T-shape rotor brake, b) proposed multi-pole multi-T-rotor brake

The maximum field-induced torque, for multi-pole multi-T-rotor MRB, is given by:

$$T_{\tau} = \sum_{1}^{k} 8 \cdot \pi \cdot l \cdot \tau_y \cdot R_o^2 \quad (1)$$

where k and l are the number and the length of the multi-T-element layers, τ_y is the maximum shear stress in a specific MRFs` layer and the R_o is the outer radius of the individual multi-T-element layer, Fig. 3 b). Similarly, the maximum viscous torque is:

$$T_{\eta} = \sum_{1}^{k} 8 \cdot \pi \cdot l \cdot \eta \cdot \frac{\dot{\theta}}{g} \cdot R_o^3 \quad (2)$$

where η is the fluid viscosity in the absence of magnetic field, $\dot{\theta}$ is the rotation velocity and the g is the MRFs` gap size.

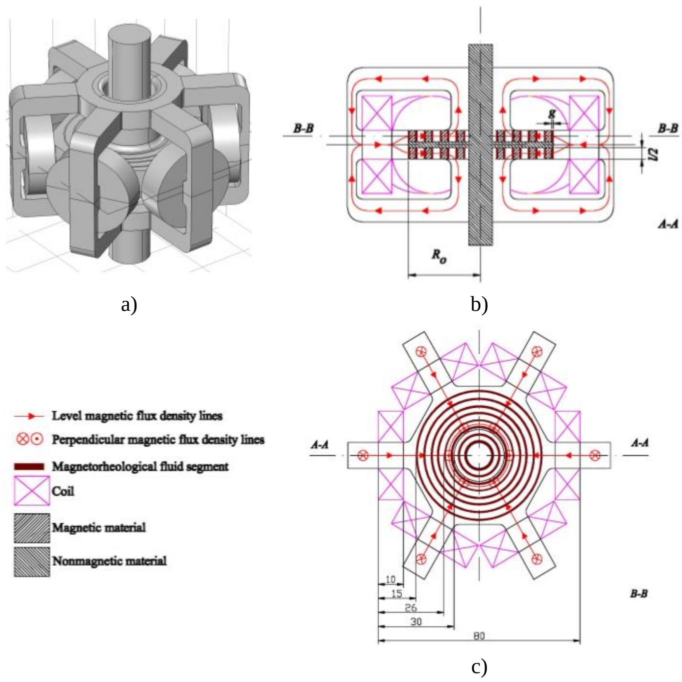


Fig. 3 Proposed magnetorheological brake layout, a) 3D model, b) and c) cross sectional illustrations

A brief parameters overview of the proposed MRB design is presented in Tab. I. Proposed MRB is planned to be manufactured in near future.

III. Numerical Simulations

In this section, the proposed MRBs' numerical simulation most important steps are presented. The proposed MRB design was modeled using commercial FEM software, *COMSOL Multiphysics*. Due to presence of the nonmagnetic disk and two six-spoke magnetic flux density return bridges, *COMSOL*'s 3D space dimension option was selected. Magnetic field was considered to be static, so the Stationary Study was used.

A. Simulation steps

Entire MRB model was surrounded with a spherical air boundary, approximately five times the volume of the proposed MRB model. Appropriate material node was assigned to every element of the model. Materials, such as nonmagnetic air and aluminum were selected from *COMSOL*'s material database, but nonlinear magnetic materials, C15E and MRF, were defined using previously measured magnetic properties data, [4]. These data have been loaded to the *COMSOL* as separate files. Note, presence of elements such as ball bearings were neglected because of their steel composition and small volume share in overall construction.

In Magnetic Fields subsection of the model, additional Ampère's Laws were needed, due to the use of several different materials. In the same subsection, six Multi-Turn Coil domain nodes were added. These nodes contain coils input data and were used to solve the following equations:

$$\nabla\times\left(\mu_0^{-1}\cdot\mu_r^{-1}\cdot B\right)-\sigma\cdot v\times B=J_e \tag{3}$$

$$B=\nabla\times A \tag{4}$$

$$J_e=\frac{N\cdot I_{coil}}{A}\cdot e_{coil} \tag{5}$$

TABLE I. PROPOSE MAGNETORHEOLOGICAL BRAKES` DESIGN PARAMETERS

Parameter	**Value**
Magnetorheological brakes' outer diameter (mm)	104
Magnetorheological brakes' length (without shaft) (mm)	54
Hexagonal prism body circumference radius (mm)	30
Hexagonal prism body length (mm)	10
Multi-T-element outer radius (mm)	24.5
Total magnetorheological fluids' active area length (mm)	32
Nonmagnetic disks' thickness (mm)	2
Nonmagnetic disks' radius (mm)	24.5
Shafts' radius (mm)	4
Total magnetorheological fluids' gap (mm)	4
Number of coils (-)	6
Number of turns per coil (-)	120
Max. control current intensity per coil (A)	1

In Fig. 4, the proposed MRBs` meshed model is presented. Mesh was generated using the User-controlled mash. The MRB core segment was meshed using the Free tetrahedral with custom element size. The maximum and the minimum tetrahedral element size were 11 mm and 0.05 mm, respectively. The solver was stationary but non-linear.

To depicture the magnetic flux density spreading patterns and its values along specific lines, across surfaces (slices) and in all three directions (volume) several 3D and 1D Plot Groups were utilized. In the 1D Plot Group line graphs were used to present magnetic flux density values changes along three straight and four circular lines. Each straight line starts from the outer MRBs` rim, passes through coils' core, then through hexagonal prism, through second coils' core and ends on the opposite rim side of the brake. These three lines were elevated from its original work plane, so that the changes in magnetic flux density could be observed without interference of the nonmagnetic disk that was in original the XY plane. Each one of the four circular lines represents magnetic flux densities values in the middle of particular MRFs` segment. A 3D Slice options were selected and defined over two appropriate planes: XY and ZY. All 3D and 1D plot results are presented in the next section.

IV. Results And Discussion

In this section, FEM simulations results are presented. FEM simulation results are presented in the form of line graphs, Fig. 5 a) and b). These figures depicture magnetic flux density changes along three straight lines that are passing through the brake in the XY plane level. Corresponding lines and dimensions are presented in Figure 3.

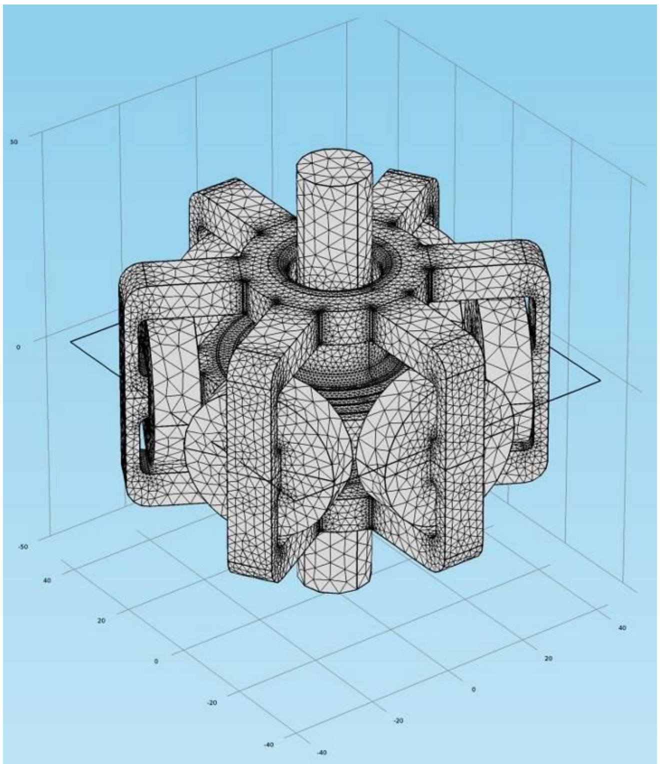


Fig. 4 Proposed magnetorheological brake meshed model

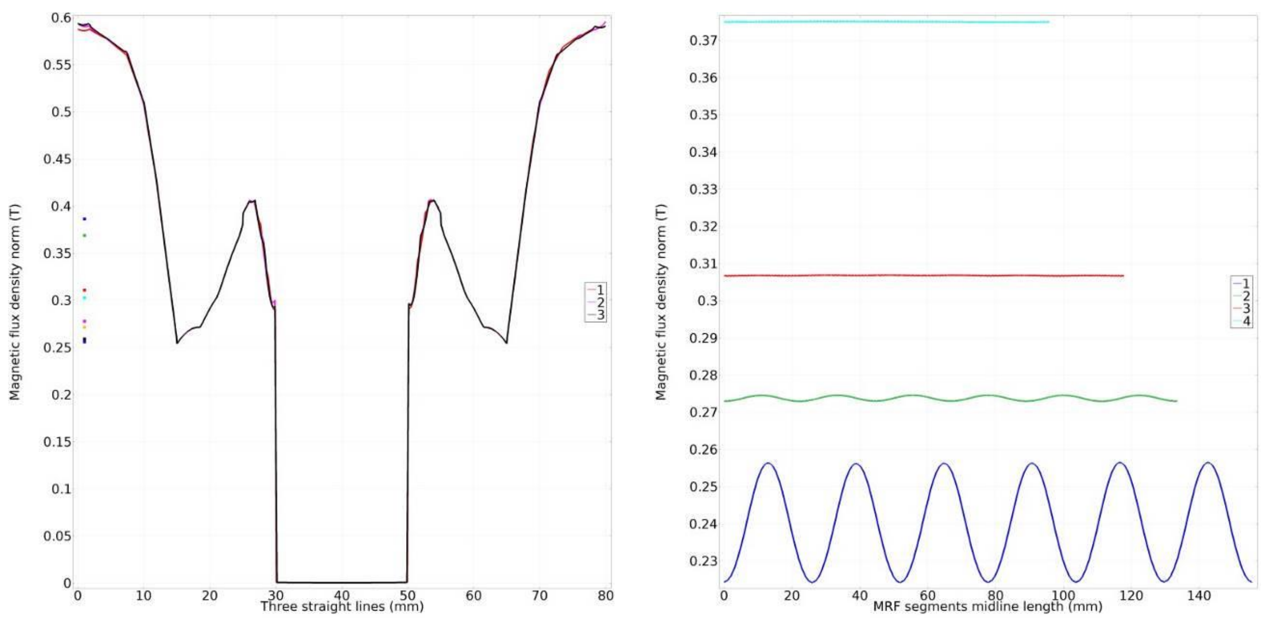
A good results repeatability and overall curve symmetry can be observed. Along these straight lines magnetic flux density changed but with noticeable drops. These drops resulted from the MRBs` cross-section area changes along the mentioned directions. Looking at the symmetrical curve at Fig. 5 a), first 40 mm span, from 0 mm to 10 mm (coil's core segment), there is almost linear, drop in magnetic flux density value. At 10 mm point, there is an abrupt change, resulted from cross section area change - from coils' core to hexagonal prism outer rim. Segment stretching from 10 mm up to 15 mm is the hexagonal prism outer rim layer (ring). This segment, of the MRB, has larger cross-section area then the previous segment (coils' core), and that allows for magnetic flux density value to drops significantly. From 15 mm up to 26 mm there is a significant increase in magnetic flux density value due to reduction of the MRBs' cross-section areas and summation of all six magnetic flux densities, which is very favorable in terms of torque generation. After 26 mm point there is another magnetic flux density value drop. This drop results from magnetic flux density lines routing towards the six-spoke return bridge.

Fig. 5 b) present magnetic flux density change inside the MRFs` segments, along four midline curves, each associated to one MRF segment. A steady increase in value is noticeable. MRF segment, closest to the outer rim of the MRB has the largest magnetic flux density intensity oscillations. The proximity of the largest MRF layer to the successive coils layout was the main reasons for these oscillations. The closer the MRF segment is to the center of the MRB, the lesser the oscillations are and the higher magnetic flux density values become.

Fig. 6 a) and b), provide in plane magnetic flux densities spreading patterns results. Two perpendicular planes were used: XY and ZY. XY plane was laid parallel with hexagonal prism but was elevated 3 mm, from its original position, in z direction. ZY plane slices perpendicularly hexagonal prism, two coils, coils' cores and two pair of six-spoke magnetic flux density return bridges.

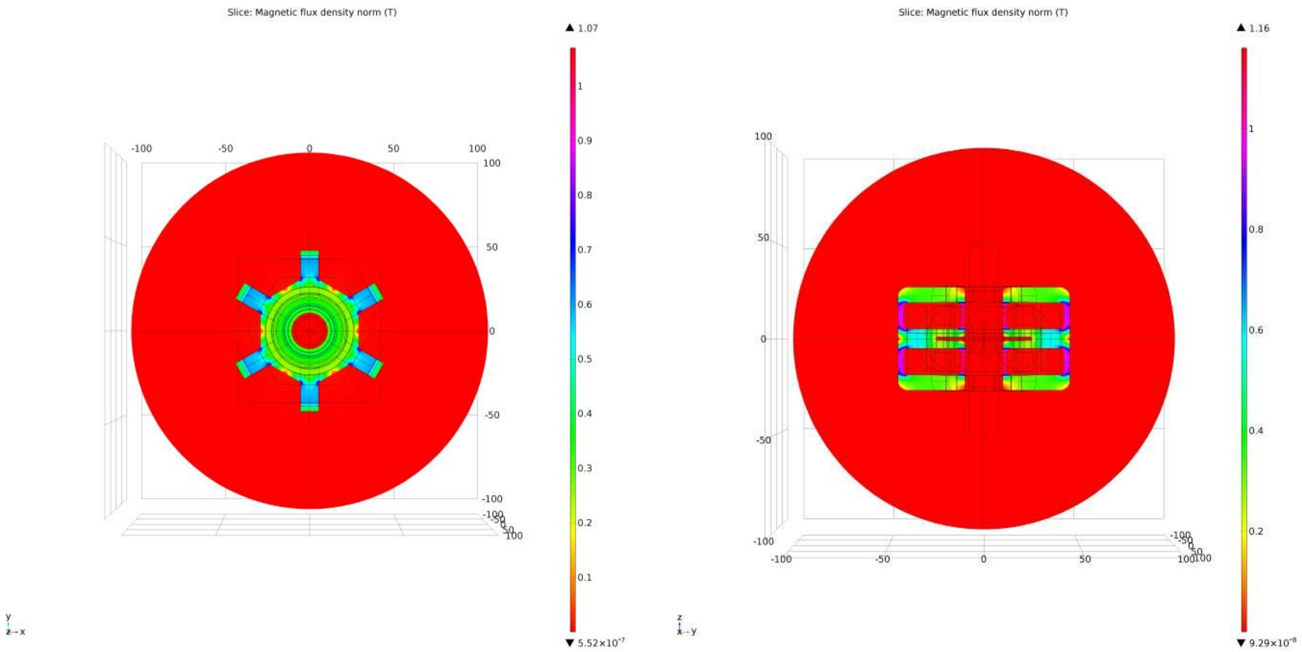
Overall magnetic flux density, in these planes, ranged from $9.29e^{-8}$ T up to 1.16 T. Parts of the proposed MRB that were of interest for this research are the MRF layers and the coils` cores. To induce the maximum shear stress, thus the maximum braking torque, the magnetic flux density needs to be as high as possible. On the other hand, high magnetic flux density will lead steel into saturation. So, a compromise was needed. Due to its single material content, small cross section area and the absence of the moving parts, coils' cores and return bridge spokes, may be exited to the maximum. In these soft steel elements, magnetic flux density will be at its allowed peak. In any other part of the brake, the dual material presence, larger cross-sectional areas and the clearance will lower magnetic flux density values.

To present magnetic flux density spreading patterns in all three directions (X, Y and Z), a 3D surface spreading patterns were generated and the results are presented in Fig. 7. It is noticeable that the magnetic flux densities value increases in reduced cross-sectional segments of the brake, such as magnetic return bridge and coil's cores



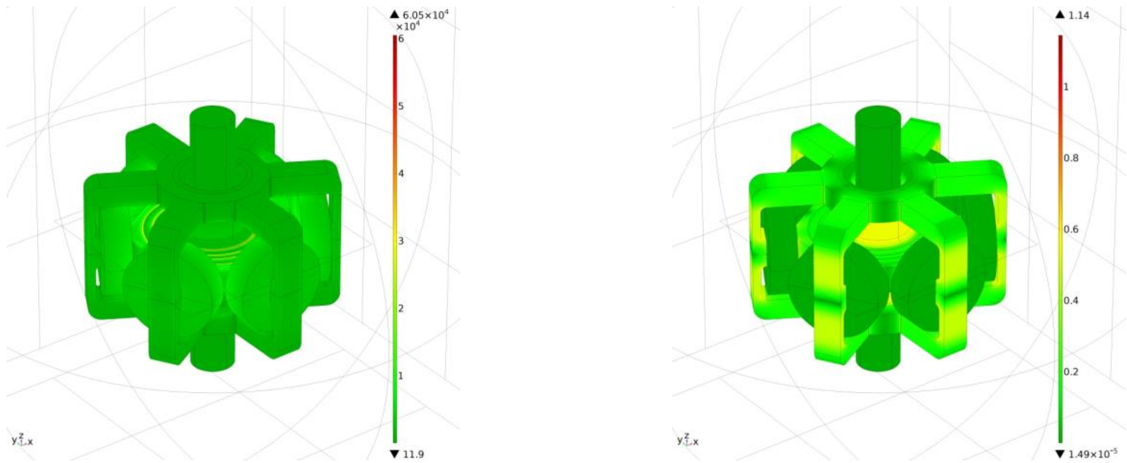
a) b)

Fig. 5 Magnetic flux density change along specific lines, a) three straight lines, b) four midline curves



a) *b)*

Fig. 6 Magnetic flux density spreading patterns, a) XY plane, b) ZY plane



a) *b)*

Fig. 7 3D presentation of spreading patterns for: a) the magnetic field, b) magnetic flux density

V. Conclusion

A new magnetorheological brake design is proposed. Magnetic flux density values over specific lines, areas and volume were obtained using FEM software. Nonlinear relationship between magnetic flux density and magnetic field in different materials was applied in the simulations. The proposed multi-pole multi-T-rotor magnetorheological brake design shows big potential. Greater braking torque, in constrained volume and weight, is now achievable.

Acknowledgment

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