A contribution to the analysis of magnetorheological brake

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Abstract. Greater braking torque, in constrained volume and weight, is a primary challenge in magnetorheological brakes` designs. This paper deals with the feasibility of increasing the overall braking torque by multiplying the number of its active surfaces in constrained volume. Improved design of magnetorheological brake is presented. Variation in number of active surfaces and their influence to magnetic flux density intensity was considered through electromagnetic simulations. Simulations on multiple models were carried out using commercial finite element method software - *COMSOL Multiphysics*, AC/DC module. Materials` magnetic properties, required for simulation process, were previously obtained from manufacturer or were determined by the measurements and were applied to the simulations. Post processing was utilized to calculate the magnetic flux density distribution and intensities across the models` specific cross-sectional areas. The proposed magnetorheological brake design shows great potential for braking torque increase.

1. Introduction

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

There are several MRB types [3]. Regardless of their construction differences, the direction of magnetic flux density is their common feature. The magnetic flux density - magnetic flux direction is and needs to be perpendicular to MRF`s flow direction i.e. MRF`s active surfaces 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. Magnetic properties of a MRFs` can easily be obtained from their manufacturers. 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 property was tackled earlier and is presented and explained in details in [4].

The major issue with any MRB`s application, e.g. robotics, automotive, industry etc. is that the overall braking torque value is still far too small. There are several ways to increase its value. One of them is to use MRFs with better yield characteristics and to reduce MRF`s gap size inside the brake.

Second is to increase the applied magnetic flux intensity acting on the MRF. The last one is to enhance the size of the MRF`s active surface area by multiplying the number of its layers.
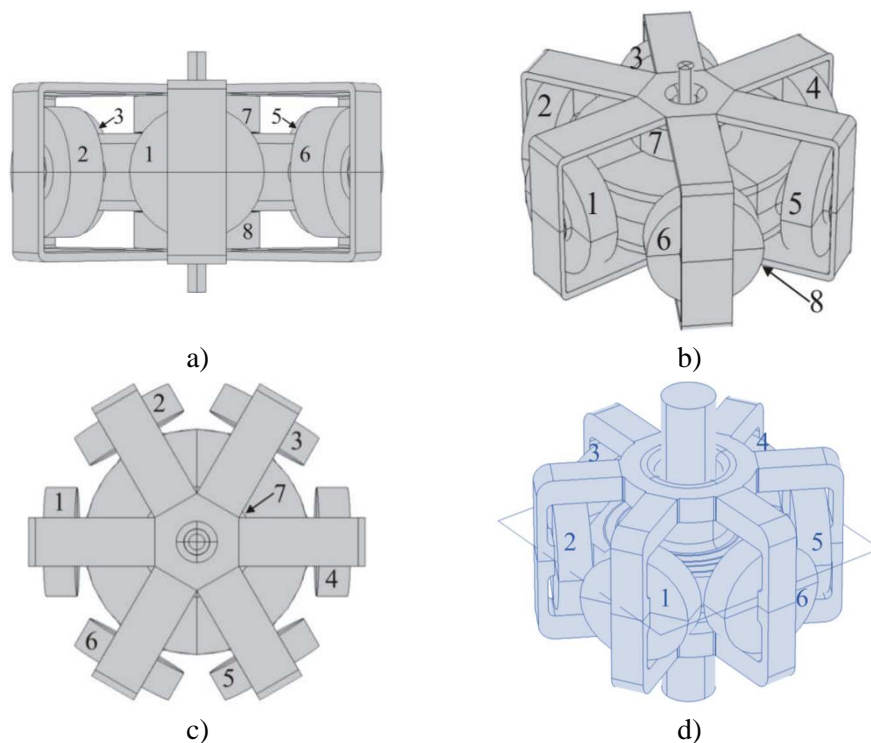
The objective of this work was to simulate magnetic flux distribution through variable number of MRF layers of a novel MRB design that features some of the above-mentioned braking torque improvement techniques. The magnetic flux distribution was analyzed by a commercial Finite Element Method - FEM software. Obtained magnetic flux values can then easily be converted into braking torque values.

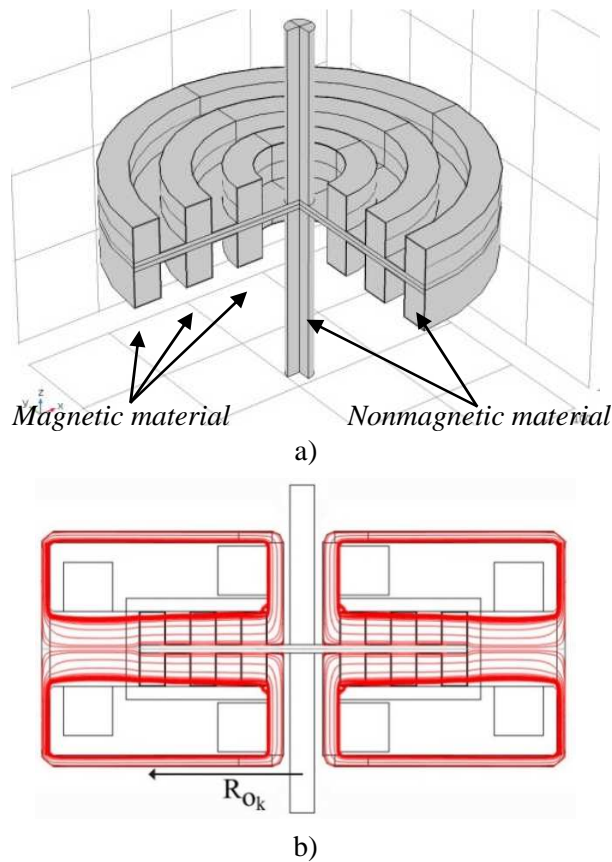## 2. Novel magnetorheological brake design

The authors of this paper have used previous, [3], MRB`s type division: drum, inverted drum, disc, T-shape rotor and multiple discs MRB. There are design variations for each type. The MR disc brake design is very common MRB type found in literature today [2, 3], but the emphasis of this research was placed on the hybrid design, combining the drum and T-shape rotor brake design.

2.1. Proposed design

Newly propose MRB design, Figure 1 a), b), c), is a design variant of the drum and the T-shape rotor design. Opposed to MR drum brake type, that only has one coil, or oppose to the MR T-shaped rotor brake, that has two separate coils, proposed design now has several more (eight) individual stationary coils, thus forming a multi-pole structure. This is a design improvement compared to previously proposed design in [4], Figure 1 d). Novel MRB design has eight excitation divided into two sets. First set of coils, in Figure 1 marked 1 - 6, are radially arranged on the circumference of a MRB`s stator. Second set of coils, in Figure 1 marked 7 and 8, are positioned parallel to rotor`s shaft axis. Each coil`s magnetic flux vector - $\vec{B}$ is directed towards the center of the MRB, thus increasing the magnetic flux intensity acting on the MRF contained inside the brake. To have a closed magnetic circuit, there are two six-spoke magnetic flux density return bridges, Figure 1.

a)   b)

c)   d)

Figure 1. Magnetorheological multi-pole multi-T-rotor brake designs, a), b), c) novel design, d) previous design [4].

Magnetic material   *Nonmagnetic material*

a)

b)

Figure. 2. Proposed magnetorheological brake design cross section ilustrations, a) multi-T-rotor assembly, b) magnetic flux spreading routes (layers).

To increase the total MRF active surface area, T-rotor element was concentrically multiplied several times inwards, thus forming a new multi-T-rotor element, Figure 2 a).

Proposed MRB multi-T-rotor assembly, i.e. shaft and multi-T element, is composed of both nonmagnetic and magnetic materials. Nonmagnetic shaft also features nonmagnetic disk, designated as multi-T-element inner support. The nonmagnetic disk diverts magnetic flux lines spreading route through body of the MRB, and splits it into two magnetic flux layers, Figure 2 b). These two layers act uniformly onto separate but geometrically equal segments of the MRF active surfaces i.e. MRF layers.

2.2. Mathematical model

The proposed MRB design torque generating properties can be described by the same analytical model used for the MR drum brake model with the results adjustment for additional MRF layers. The maximum field-induced torque, for MR drum brake, is given by:

$$T_\tau = \sum_1^k 2 \cdot R_{o_k} \cdot \left(2 \cdot \pi \cdot R_{o_k} \cdot l\right) \cdot \tau_y = \sum_1^k 4 \cdot \pi \cdot l \cdot R_{o_k}^2 \cdot \tau_y \tag{1}$$

Similarly, the maximum viscous torque is:

$$T_\eta = \sum_1^k 4 \cdot \pi \cdot l \cdot \eta \cdot \frac{\dot{\theta}}{g} \cdot R_{o_k}^3 \tag{2}$$

where, k is the number of MRF layers, R_{o_k} is a radius of a specific MRF layer, l is the MRF layer`s height, τ_y is the yield stress developed in response to the applied magnetic field, η is the viscosity of

the MR fluid with no applied magnetic field, $\dot{\theta}$ is the angular velocity of the rotor and g is the thickness of the MR fluid gap.

It is anticipated that the overall intensity of the B will increase as progressed toward inner MRF layers, leading to increase of the τ_y in inner MRF layers. On the other hand, the R_{o_k} will progressively decrease in radius. This combination may result in an even MRF layer induced torque value distribution i.e. even overall torque contribution from each of the MRF layers. Magnetic flux intensity simulations results are presented in this paper.

A brief parameters overview of the proposed MRB design is presented in Table 1. Proposed MRB model is planned to be manufactured in near future.

3. Numerical simulations

In this section, the proposed MRB`s 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 utilized. Magnetic field was considered to be static, so the Stationary Study was used.

3.1. Simulation steps

Entire model should be surrounded with an air boundary, several times the volume of the model. Appropriate material nodes are to be assigned to every element of the model. In this specific simulation, materials such as nonmagnetic air and aluminium were selected from *COMSOL*`s database, but nonlinear magnetic materials, such as C15E steel and MRF *Basonetic 5030*, were defined using previously obtained 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, [5]:

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

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

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

Table1. Multi-pole multi-T-rotor magnetorheological brake parameters.

Parameter	Value
Magnetorheological brakes` outer diameter (mm)	315
Magnetorheological brake`s length (shaft not included) (mm)	94
Multi-T-element outer radius (mm)	100
Magnetorheological fluid`s active area height (mm)	20.5
Nonmagnetic disks' thickness (mm)	2.5
Shafts' radius (mm)	7.5
Magnetorheological fluid gap (mm)	0.5
Number of coils (-)	8
Maximum control current intensity per coil (A)	1

One of three meshed model is presented in Figure 3. Mesh was generated using the *User-controlled mash*. The MRF`s layers were meshed using the *Free tetrahedral* with custom element size. The minimum tetrahedral element size was at 0.05 mm. Also, special attention was placed on the curvatures and the narrow regions of MRF segments of the brake. The curvature radii were multiplied by the *Curvature factor* parameter which in return gives the maximum allowed element size along specific boundary. The *Resolution of narrow regions* parameter controls the number of element created in narrow regions. These parameters greatly improved the mash quality of the models, which is now at the threshold of 0.1, which is considered satisfactory mesh. The solver was stationary but non-linear.
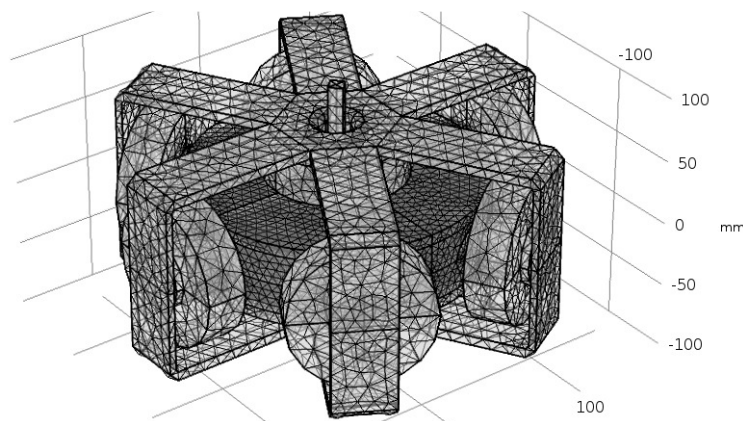
3.2. Simulation goal

The goal of this research was to analyse the influence that the change in the number of the T-rotor elements has on magnetic flux and to compare the results. For that purpose, three FEM MRB models were constructed. All models had the same number and the same specific position of the coils as well as the identical basic construction and the parameters of the brake.

Main difference between the models was the number of the T-rotor elements, Figure 4. The first model had only two T-rotor elements i.e. four MRF layers. The second model had three T-rotor elements i.e. six MRF layers and the third model had four T-rotor elements i.e. eight MRF layers.
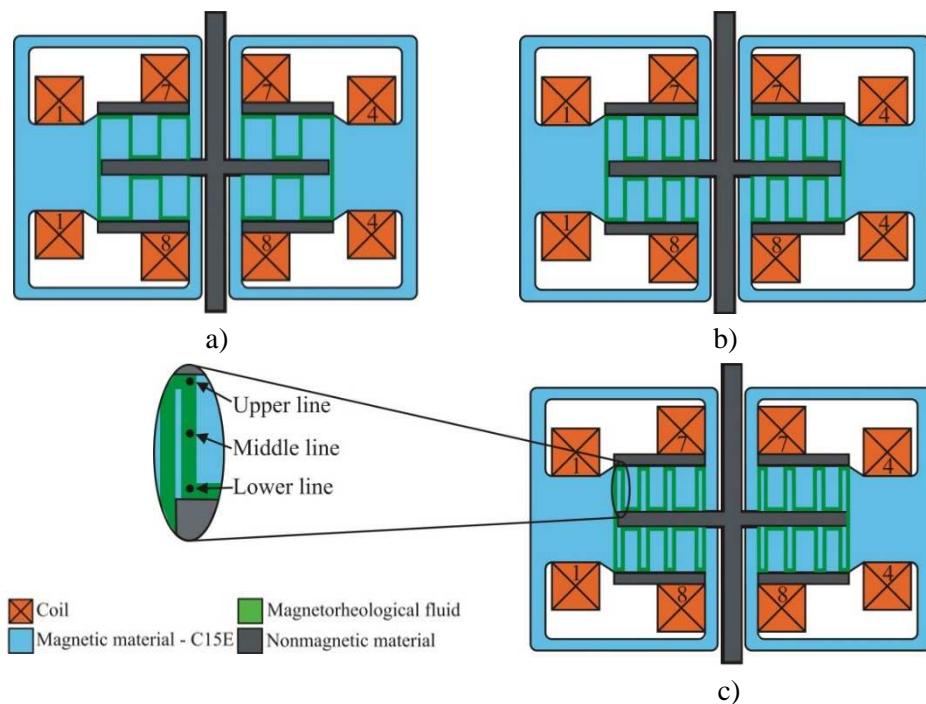
With the increase in the T-rotor element number, the number of the MRF layers, which generate the overall torque, increases as well. With the increase in MRF layers number the MRF volume increases but the volume of the volume of the ferromagnetic material decreases. With the ferromagnetic material volume share in decline, magnetic flux density intensity, potentially, decreases. As a result of this the overall torque value may decrease as well. On the other hand, if the number of MRF layers were to be reduced, the number of MRF active surfaces will reduce as well. As a consequence of this reduction, the ferromagnetic material volume share raises leading, potentially, to increase of the magnetic flux density intensity.

To determine the overall magnetic flux density intensity in a specific MRF layer a series of FEM simulations were carried out for each of the three MRB models. A median magnetic flux density value was determined along three predetermined circular lines. *A 1D Plot Group* line graphs were used to depicture magnetic flux density magnitude changes along these three circular lines. Circular lines were positioned at the very bottom of the MRF layer, at the very top of it and in the middle of it, Figure 4 c).

In the simulations, the hexagonal prism stator, the coils' cores, the multi-T-rotor element and the six-spoke magnetic flux density return bridges were assigned with the magnetically soft steel C15E. The rest of the MRB assembly elements were assigned with nonmagnetic materials.

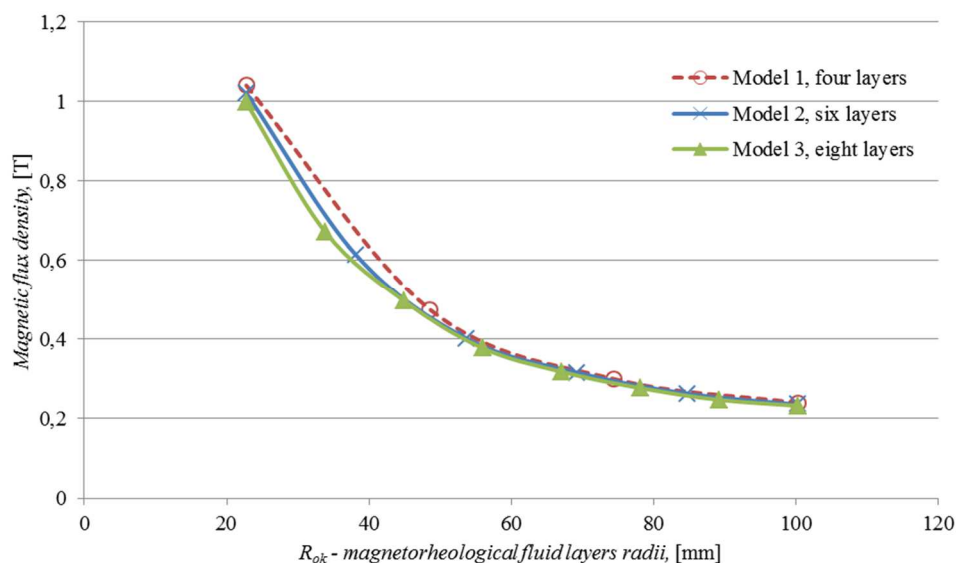**Figure 3.** Proposed magnetorheological multi-pole multi-T-rotor brake`s mesh.

Figure 4. Proposed magnetorheological multi-pole multi-T-rotor brakes cross sections illustrations, a) Model 1, b) Model 2 and c) Model 3 (with circular lines points of passing illustration).
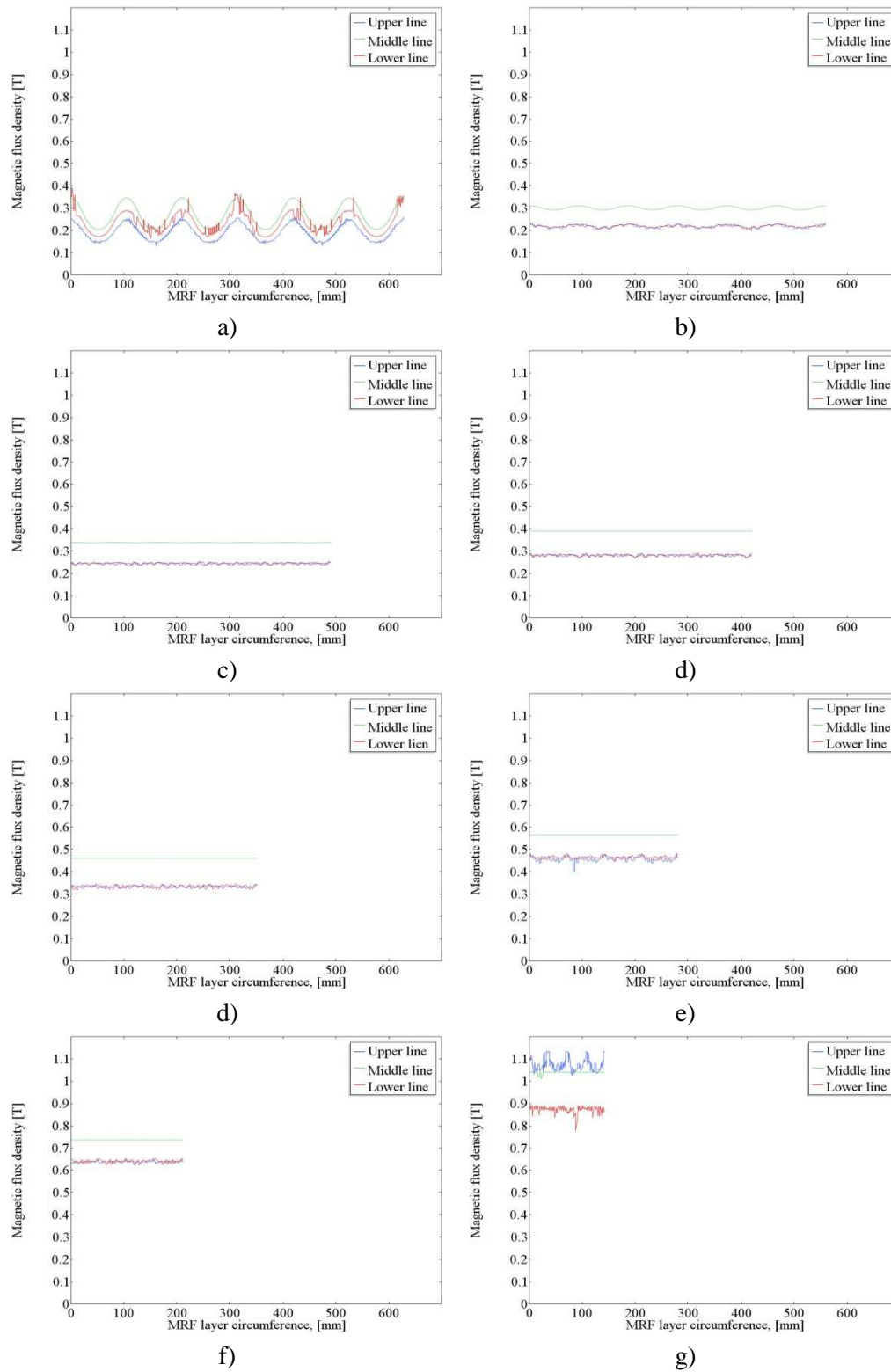
4. Results and Discussion

4.1. Magnetic flux density distribution

Magnetic flux density distribution pattern within the proposed MRBs was studied and the results are presented. Magnetic fluxes intensities changes in each MRF layer for all three MRB simulated models are presented in Figure 5 and Figure 6. Numerical values are presented in Table 2. These values were determined along three circular lines, Figure 4, for each MRF layer. Minimum and maximum values of

Figure 5. Change in magnetic flux intensity in each magnetorheological fluid`s layer for all three models.

magnetic fluxes, along these lines for all three models, ranged from 0.197 T up to 0.278 T in outer MRF layer and from 0.873 T up to 1.077 T in the inner MRF layer.

Figure 6. Magnetic flux simulation results for magnetorheological multi-pole multi-T-rotor brake - Model 3.

Good results repeatability is achieved especially in the outer MRF layers area, Figure 5. Small inconsistencies in magnetic flux results in the inner MRF area, Figure 5, are due to different spacing and different number of MRF layers between models. Non-linearity in magnetic fluxes change through MRF layers is noticeable. This may lead to non-consistency in the field induced torque values among MRF layers. This was not predicted nor considered in the early stage of the MRB design stage.

Table 2. Numerical values of magnetic flux intensities at a specific radii.

Model 1			Model 2			Model 3		
Layer	B, [T]	R_{ok}, [mm]	Layer	B, [T]	R_{ok}, [mm]	Layer	B, [T]	R_{ok}, [mm]
1	1.0402	22.75	1	1.0208	22.75	1	0.9970	22.75
2	0.4745	48.59	2	0.6122	38.25	2	0.6727	33.82
3	0.2998	74.42	3	0.4013	53.75	3	0.4975	44.89
4	0.2398	100.25	4	0.3157	69.25	4	0.3776	55.96
			5	0.2627	84.75	5	0.3182	67.03
			6	0.2355	100.25	6	0.2769	78.1
						7	0.2473	89.17
						8	0.2324	100.25

5. Conclusion

This study presented a novel viewpoint on magnetorheological brakes. A new magnetorheological brake design was proposed. By combining magnetic and non-magnetic materials, a new space may have been opened for magnetorheological technology. The use of non-magnetic material in magnetic flux density path led to its non-uniformity through magnetorheological brake's body.

The goal of this study was to determine magnetic flux density intensity change with regard to change in number of magnetorheological fluid`s layers. For this purpose three magnetorheological brake finite element models were made using commercial finite element model software. All three models had the same basic geometric properties and number of excitation coils but differed in the number of magnetorheological fluid`s layers. Magnetic flux densities intensities along specific lines were obtained for each magnetorheological fluid`s layers for all three models. Results are presented graphically and tabular.

Nonlinear relationship between magnetic flux density and magnetic field in different materials was applied in the simulations. Combination of materials may contribute to other magnetorheological applications, where there is a need for magnetic flux density increase in small areas, but where geometric restrictions are present.

The proposed multi-pole multi-T-rotor magnetorheological brake design shows big potential. Greater braking torque, in constrained volume and weight, is now achievable. Future work should be focused on linearization of magnetic flux density change through magnetorheological fluid`s layers which was not the case in this study.

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