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PROBLEMS OF FEM SIMULATION OF MAGNETORHEOLOGICAL CLUTCH'S MAGNETIC CIRCUIT

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Abstract: *The article deals with Magnetostatic analysis of a magnetorheological (MR) clutch. The analysis is needed for acquiring information about magnetic saturation of iron parts in operation mode. This paper describes a comparison of FEM model and experimentally measured data in the clutch´s working gap filled with the air. The most important parameters such as use of linear and nonlinear material (iron parts, MR fluid), element type and size, effect of measuring groove for Hall sensor on magnetic field distribution, which significantly improved the FEM model of the simulation were determined, and they are also mentioned bellow. Simulation based on the verified FEM model of magnetic circuit with MR fluid was completed. Results showed places, where it is possible to reduce the material without any changes to the magnetic flux density in the working gap. With this knowledge, we reduced the weight by 13,2%.*

Keywords: ***magnetorheological clutch, MR clutch, FEM simulation, magnetic circuit***

1. Introduction

Magnetorheological clutches are characterized by very good controllability of transmitted torque and very short reaction times. The biggest advantage over the conventional clutches lies in their X-by-wire handling without any need for a mechanism. There are two types of MR clutches (Fig. 1). Both, *disc shaped* and *bell shaped* clutch, show jump of transmitted torque in the transition from passive to active mode. On the other side, disc shaped clutch can avoid this jump by smart choice of an inner and outer radius (Lampe *et al.*, 1998; Saito & Ikeda, 2007; Kielan *et al.*, 2011; Barber & Carlson, 2010).

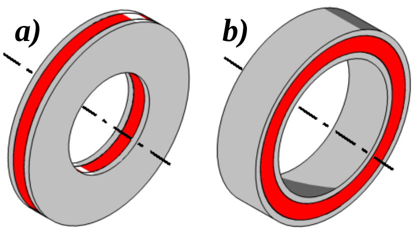

Fig. 1: Types of MR clutches: a) disc, b) bell shaped

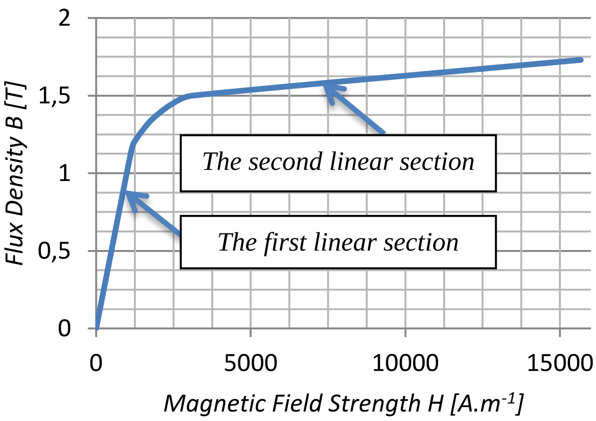

Fig. 2: Nonlinear B-H curve

Main MR clutch's components are made of steel which shows significant nonlinearity in magnetic behavior represented by *B-H curve* (Fig. 2). *The first linear curve section* shows high increase of flux density in proportion to the field strength. At some level any increase in the magnetic field strength (due to an increase in the electrical current flowing through the coil) will have little or no effect. This point, where the flux density reaches its limit, is called *magnetic saturation* and it is caused by the almost perfect alignment of tiny molecular magnets (Wayne Storr, 2013). Our goal during reducing weight is to stay in the first linear section of the B-H

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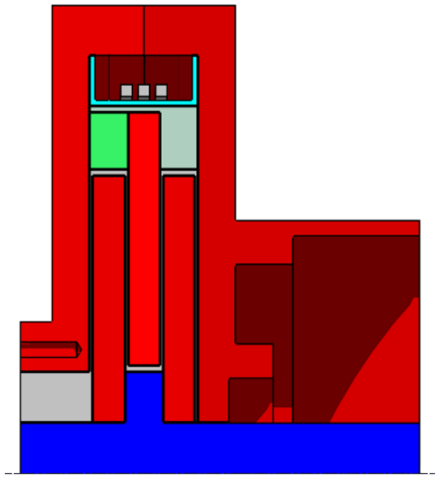

Fig. 3: Constructed MR clutch cut

curve, where the input electrical current is used in the most effective way. This limitation, caused by the magnetic saturation, applies on MR fluids (MRF) as well and therefore new and more powerful MRF are still under developement (Mrlík *et al.*, 2013; Sedlacik *et al.*, 2011).

In order to reduce calculation time, ANSYS offers 2D axisymmetric analysis. Unfortunately model of observed MR clutch couldn't be simplified, because of its nonsymmetrical features as the screws or measure groove, which have big impact on results as you can see bellow in section *Results*. We have been investigating disc shaped MR clutch with two rotor disks (Fig. 3), which with housing and stator disk are made of steel ČSN 11 523 (S355J2G3). Complete construction documentation of this MR clutch is made as a master's thesis (Nováček, 2011).

2. Methods and Procedures

First of all, the flux density in the measure groove had to be measured. For this purpose, Hall sensor *STD18-0404*; *5180 Gauss/Tesla meter* produced by *F. W. Bell* and DC power supply *Manson SDP2603* were used. MR clutch, containing coil with 100 winding turns, was demagnetized applying of alternating current field with decreasing amplitude. After that, clutch was powered by constant value of electric current 1,5A and data were measured.

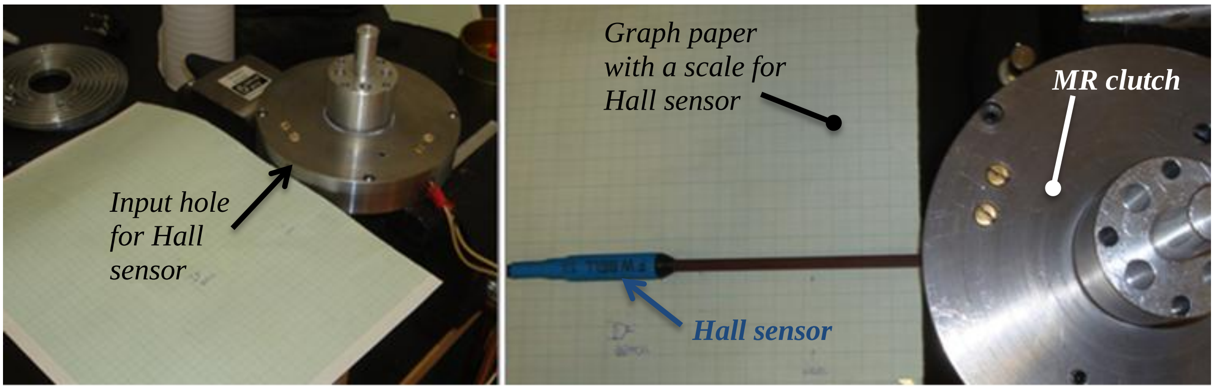

Fig. 4: Experimental assembly for measuring magnetic flux density with Hall sensor

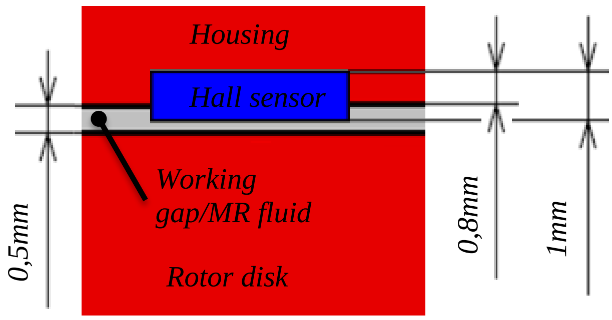

Fig. 5: Measure groove detail

As you can see in the Fig. 5, Hall sensor's thickness 1mm is greater than the thickness of the working gap 0,5mm. Therefore, the 0,8mm measure groove has to be created. In addition, Hall sensor is primarily meant to measure in the air surroundings - has air permeability. Sensor significantly affects magnetic field in the measure groove in MR clutch filled with the MRF, because it is the major part of the measure groove with different permeability then MRF around. That's why initial FEA were run on models with the air working gap. Only after successful solution of these analyses, comparison of computed and measured data can be made. Complex information about magnetic field of MR clutch filled with MRF can be obtained only by FEA.

Four FEM models with a different level of geometry details were studied, finding out which feature cannot be simplified, because of its big impact on the obtained results:

a) *Geometry model n. 1* – no gaskets, no bearings, no screws, screw bores filled, sharp edges, simplified shape of some components for example rotor shaft (blue one in Fig. 3).
b) *Geometry model n. 2* – same as *a)*, the measure groove for a Hall sensor applied (Fig. 6). Reason: revealing the groove's influence on the flux density.
c) *Geometry model n. 3* – same as *b)*, through screw bores applied (Fig. 7a). Reason: revealing the impact of the different clutch design with 3 magnetic rotor screws; verifying simpler geometry model than actual constructed MR clutch.
d) *Geometry model n. 4* – same as *b)*, blind screw bores applied (Fig. 7b). Reason: nearing experimentally measured data.

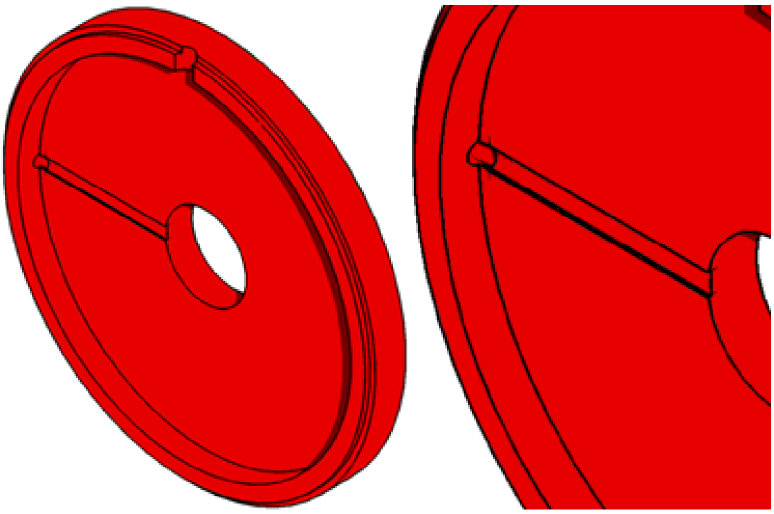

Fig. 6: Detail of measure groove

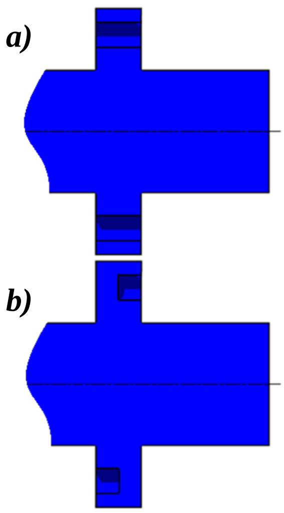

Fig. 7: a) through and b) blind screw bores in the rotor shaft

After finding most correct geometry model n.1 to n.4; element size, linear and nonlinear magnetic material and different solver types were varied. Final FEM model will be set as a compromise between hardware requirements/solving time and accuracy.

With relatively accurate FEM model, we can simulate operation mode by solving FEA with working gap filled by *MRF Lord 140 CG*. Its actual magnetic behavior (B-H curve) is taken from the manufacturer *Lord Corporation*. Results of the analysis carry information about magnetic saturation in metallic components of MR clutch. Much higher magnetic flux density is expected, because of MRF's approximately 6 to 10 times higher permeability than air. If some parts lie within the first linear section of B-H curve (Fig. 2), these components can by lightened. On the other side, weight cannot be reduced in components lying after magnetic saturation point.

Next, design of MR clutch weight relief is verified by FEA. Only after simulation, reducing weight is actually done on existing MR clutch. At last, we measure the flux density in the air filled lightened clutch using Hall sensor and compare obtained data with FEA results.

3. Results

<u>*Geometry*</u>

a) Geometry model n. 1: FEA magnetic flux density results are extracted from the path placed in the middle of the working gap. On the other side, experimentally measured data are, because of premise that Hall sensor measures the flux density in the middle of its 1mm thickness, from the path placed 0,5mm from the bottom of the measure groove (Fig. 5). As you can see on the graph (Fig. 11), results don't match at all. Peak from FEA is 251% of nominal value (measured data).

b) Geometry model n. 2: new added measure groove significantly lower the magnetic flux density. FEA peak value drops to 137% of nominal value (measured data). In this geometry model, experimentally measured and calculated data come from the same path. Results show groove's behavior as the resistance in the magnetic flux. Groove's impact on the air filled working gap is shown in Fig. 8.

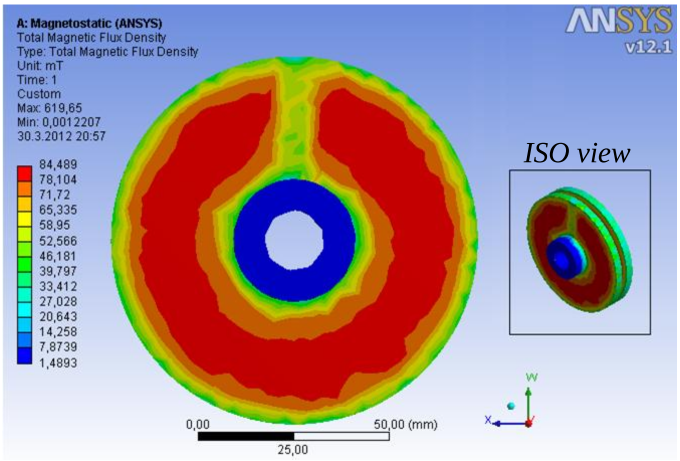

Fig. 8: Affect of measure groove on magnetic flux density in working gap

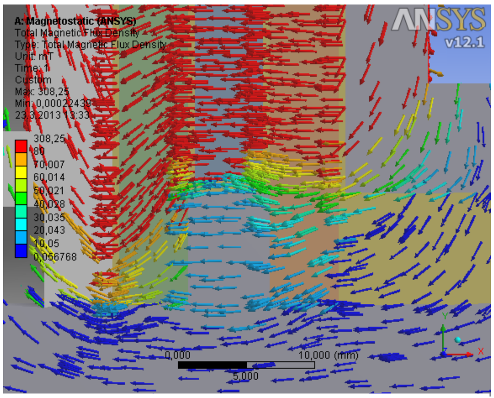

Fig. 9: Direction of magnetic flux density flow in rotor and clutch disk area in geometry model n.2

c) Geometry model n. 3: <u>through</u> screw bores reduced the top magnetic flux density by 18%. As in previous geometry model, FEA peak value drops, this time to 112% of nominal value (measured data). Reason for considering through screw bores is to simplify design and thought that magnetic saturation of rotor screws will have little effect on magnetic circuit because they are relatively far from the source of magnetic field – coil. However, these predictions did not fulfill and therefore using through screws <u>is not</u> recommended as improving clutch design.

d) Geometry model n. 4: <u>blind</u> screw bores represent actual geometry of MR clutch more realistic. This FEM model resulted in the reduction of the magnetic flux density to difference between peaks values 2% - FEA peak value is 102% of nominal value (measured data). Explanation of this effect is clear from the figures of directional magnetic flux density. In case of *<u>blind</u> screw bores model* (Fig. 10b), magnetic flux has to bypass the whole rotor shaft, because of its low permeability (stainless steel). On the contrary, in *<u>through</u> screw bores model* (Fig. 10a), magnetic flux flows through the bores and therefore acts as a less retarded. In other words, through screw bores result in the short of magnetic flux, decreasing magnetic resistance – higher magnetic flux density in the measure groove.

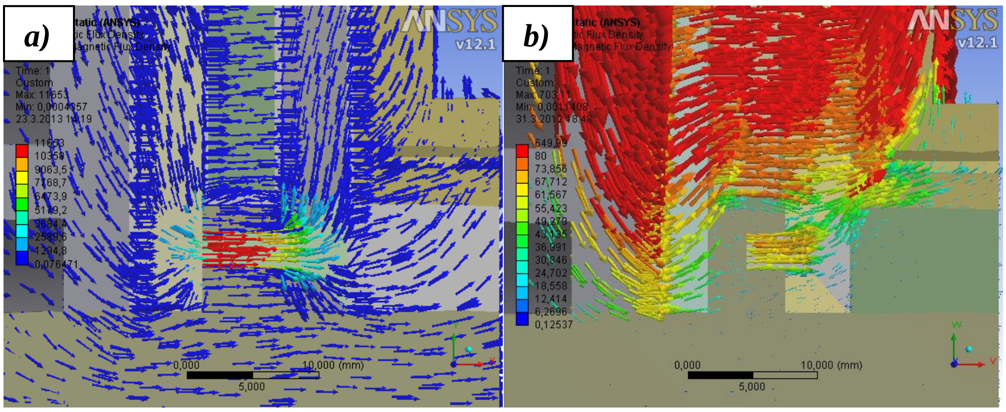

Fig. 10: Direction of magnetic flux density flow in a) through and b) blind screw bores (note: contour scales are not the same for a) and b) in effort to highlight the short effect)

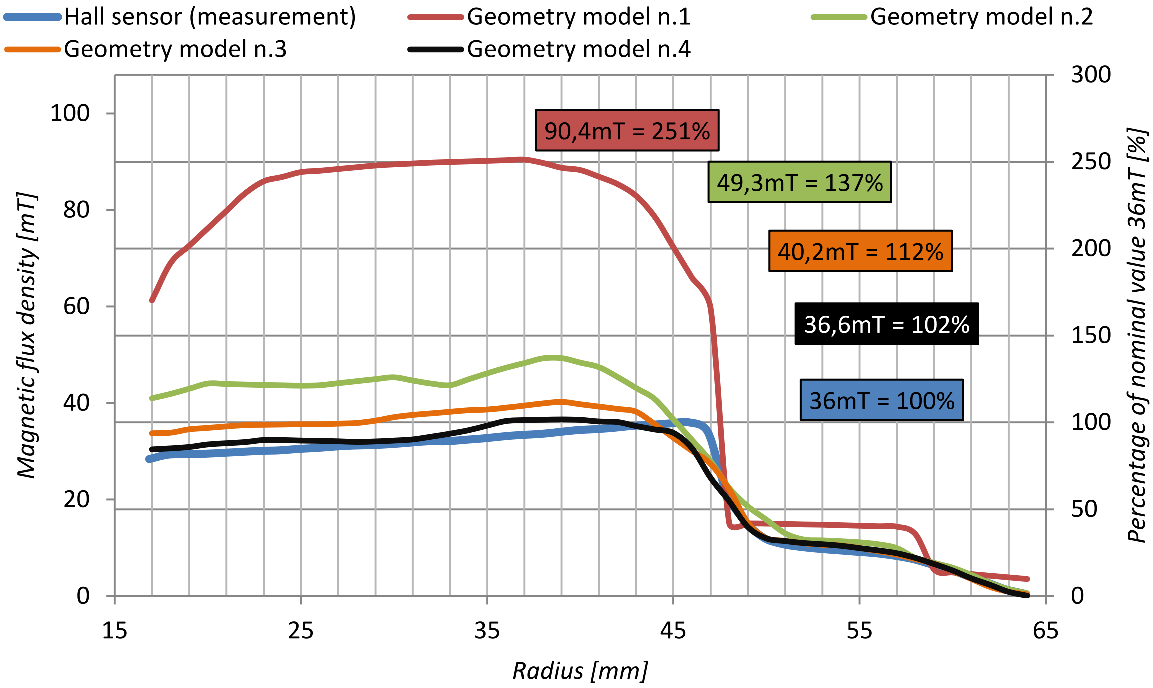

Fig. 11: Comparison of different geometry models with experimentally measured data

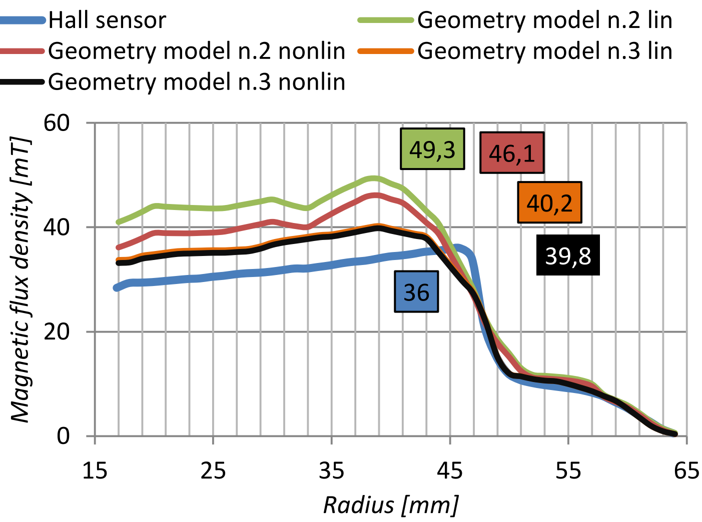

Fig. 12: Impact of nonlinear material on accuracy of the FEM model

Magnetic linear and nonlinear material

Magnetic nonlinear material can rapidly increase solving time, but it also can radically accurate FEA results. Linear and nonlinear material was used for *housing* and *clutch disks* on geometry model n.2. Nonlinear material on these components useful improves FEM model (Fig. 12). In addition *housing* and *clutch disks* literally have to be nonlinear, because the magnetic saturation point of these parts is used as the main weight reducing criteria. Next, nonlinear material for *rotor screws* on geometry model n.3 with nonlinear housing and clutch disks was investigated. Change in magnetic flux density is not so significant (Fig. 12). According to much higher solving time needed for solving this FEA with nonlinear rotor screws and poor FEM model improvement, linear rotor screws are accurate enough.

Mesh density

3 mesh density applied on geometry model n.4 were observed: *Coarse* (375 934 elements), *Medium* (754 517 elements) and *Fine* (1 724 289 elements). According to accuracy (Fig. 13) and hardware requirements, the most appropriate mesh is set to *coarse* model.

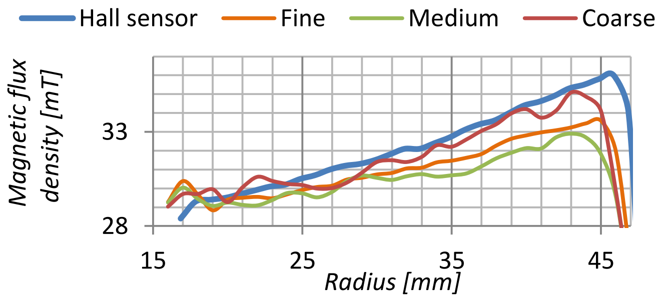

Fig. 13: Different mesh models

FEA of MR clutch filled with MRF

According to the previous experiences with various geometry model, mesh density and linear/nonlinear material, we find accurate FEM model of the magnetic circuit of the MR clutch (for more information see section *Conclusions* bellow), which we use on the MR clutch with MRF working gap. As said before, this MRF filled MR clutch cannot be measured experimentally by Hall sensor. After solving FEA, results are shown in Fig. 14. The FEM model with MRF has much higher magnetic flux density than model with an air working gap. The flux density limits weight reducing possibilities.

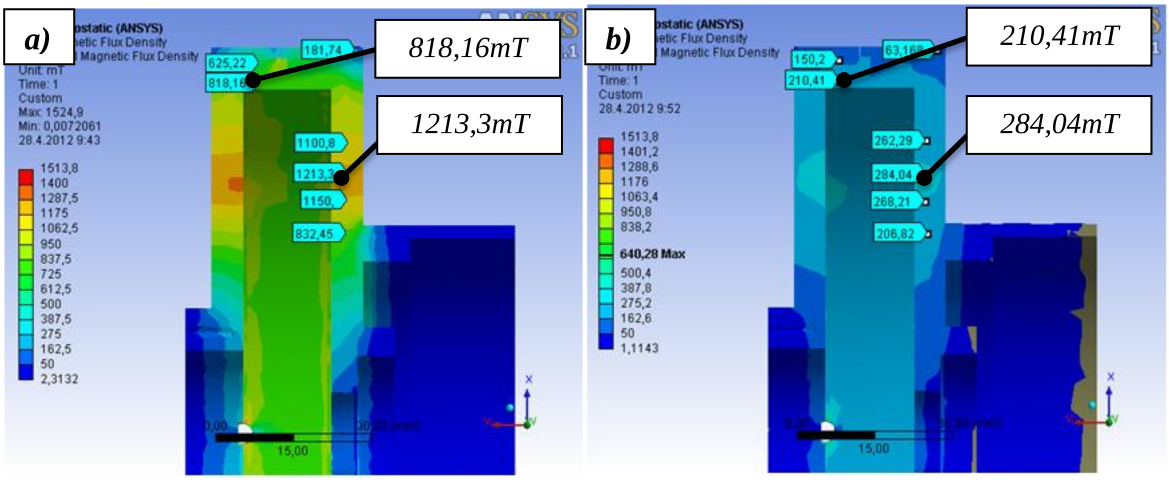

Fig. 14:Magnetic flux density in clutch filled by: a) MR fluid, b) an air

Weight reducing

The peak of the first linear section (Fig. 2) of B-H curve was set from *Ansys v12.1* material data sheet of *Steel 1018 90.5 HRB* to 0,9T. In other words, the clutch components made of steel can be lightened only if its magnetic flux density does not exceed 0,9T. The parts of our concern are the heaviest parts such as housing, stator and rotor disks.

Housing reaches its magnetic saturation, while in operation mode, at the face areas (Fig. 14), but the outer radius area has the magnetic flux density low enough to allow us to reduce 2mm of the diameter. FEA results and comparison with experimentally measured data (air filled MR clutch) are shown in Fig. 15.

The magnetic flux density flows perpendicular to *the rotor and stator disks* (Fig. 16) and therefore reducing thickness of these parts has no effect on its flux density, which lies within the first linear section of B-H curve. It can be said that thickness is limited by structural load. To prove this prediction, two rotor disks' thickness is reduced by 2mm. After successful solution of FEA, results (Fig. 17) confirm premises. Due to ongoing tests on constructed MR clutch, this weigh reduction could not be realized experimentally, because it influences geometry of the most of the other clutch components.

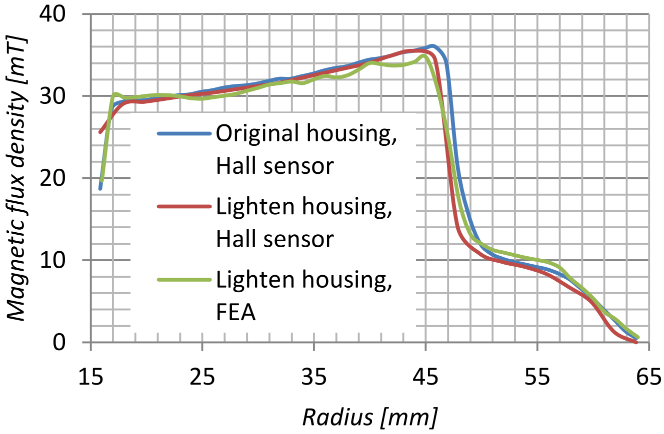

Fig. 15: Magnetic flux density in lighten housing clutch

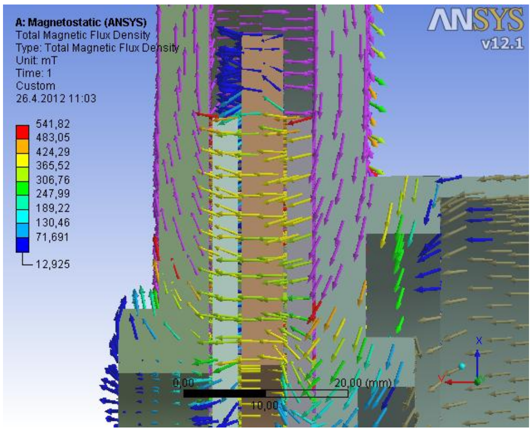

Fig. 16:Direction of magnetic flux density flow

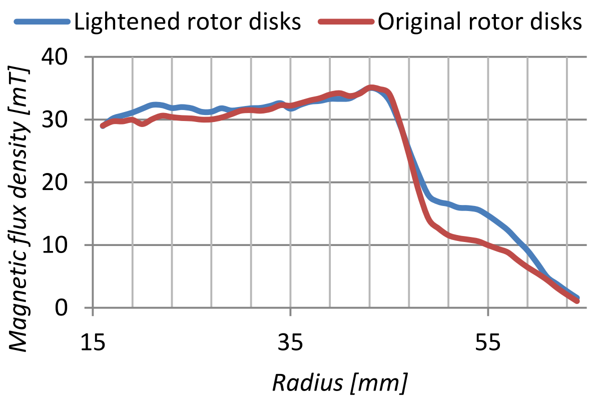

Fig. 17: FEA results comparison

4. Conclusions

Before FEA of MR clutch, only experimentally data measured in the groove with air were available. Because there was no information about magnetic field in the clutch components or during operation mode (with MR fluid), modifications' impact on the magnetic circuit was not exactly known. To sum it up, the FEA was done for these reasons:

- no information about course of magnetic flux density and saturation level inside iron components of clutch with air and MR fluid (operating conditions)
- no information about magnetic flux density in MR clutch containing the MR fluid in the measure groove and course of magnetic flux density in the working gap (outside of the groove)

This work is focused on creating FEM model of constructed MR clutch (Nováček, 2011). The most accurate model was set to *geometry model n.4* with *coarse mesh, magnetic linear* screws and *nonlinear* housing and clutch disks. Accuracy of FEA is proved by the graph in Fig. 11 and Fig. 13 where comparison with measured data (Hall sensor) is shown. FEA of MR clutch in operation mode led to reducing weight by 13,2% with minimal influence on the magnetic flux density in other parts. Thanks to this work, more MR clutch modifications can be based on knowledge of the computed magnetic circuit. According to the FEA results, *through ferromagnetic rotor screws* design is not recommended. Despite long distance between the source of the magnetic field (coil) and these screws, they cause significant short of magnetic flux. One of the next FEA improvement should be checking the magnetic behavior equivalence between FEA input material *Steel 1018 90.5 HRB* (ANSYS) and actual steel used in constructed MR clutch *ČSN 11 523 (S355J2G3).*

Tab. 1: Allowed and Not allowed simplifications of FEM model

Allowed	Not allowed
No fillets and radiuses	Geometry changes near measuring area (such as erasing measure groove)
Simplified geometry of copper coil	Magnetic linear housing and clutch disks
No gaskets and no bearings	Through screws bores simplification
Magnetic linear screws	

For more information follow bachelor’s thesis (Dlugoš, 2012).

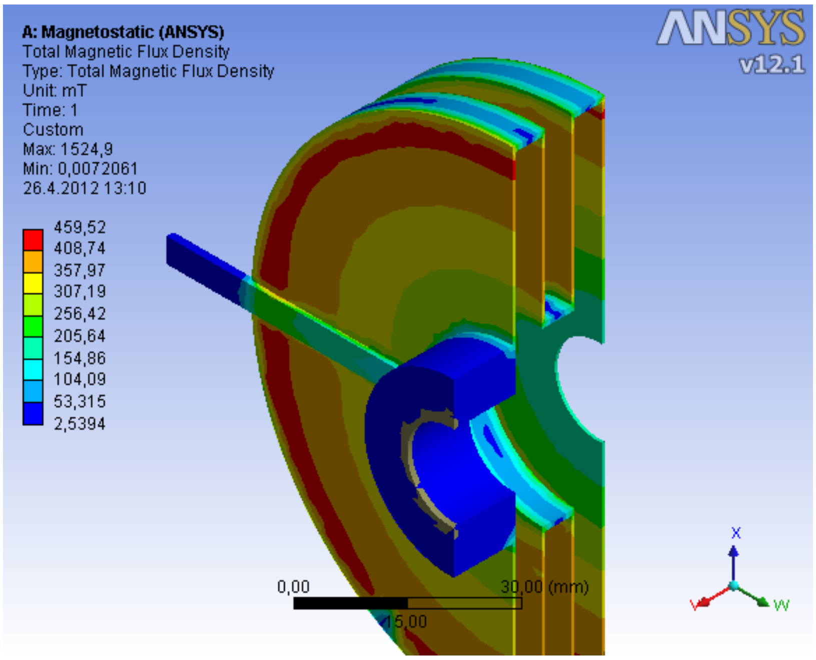

Fig. 18: Magnetic flux density in the working gap filled with MR fluid

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