ISSN 1392 - 1207. MECHANIKA. 2013 Volume 19(5): 539-543

# Theoretical research of mechanical behaviour of magneto-rheological fluid

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crossref http://dx.doi.org/10.5755/j01.mech.19.5.5527

## 1. Introduction

Design of new features in machines and devices, reducing dimensions of equipment and wide use of computer control requires implementation of materials with special properties. In order to create smart computer-controlled drives with desired dynamic characteristics, smart materials became desired in many applications. One of successful computer controlled motion application is an implementation of magneto-rheological materials in such drives. Magneto-rheological fluids (MRF) are a class of materials whose rheological properties may be rapidly altered by applying a magnetic field [1].These materials usually are liquids with magnetically polarized ferrous particles suspended in a carrier liquid. The particle size in MRFs has on the order of micrometers and is 1–3 orders of magnitude larger than the same particles in ferromagnetic fluids [2]. Main interest to MRF is caused due to their feature to change its viscosity from magnitude of applied external magnetic field as well as liquid shape change. This feature makes MRF attractive to various commercial applications, such as dampers [3, 4] and brakes [4, 5]. This paper is intended to evaluate possibility to utilize MRF for use in computer controlled actuators.

## 2. Formulation of research using finite element method

Device designing with MRF requires estimation of behaviour of MRF in static and dynamic magnetic field and possibility to reach desired characteristics. Theoretical modelling of MRF is hardly possible due inability directly to solve non-linear differential equations. The way to do that is an application of finite element analysis. From the perspective of FEA methodology, there are necessary to perform such steps for FEA in case of MRF [6] (Fig. 1):

1. Building the geometry of object;
2. Building the finite element model;
3. Solving the finite element model;
4. Analysing the results.

Mathematical modelling starts with geometry of object (Fig. 1). 2D or 3D CAD programs are mostly used for geometrical modelling. CAD model should approximately, with some boundary simplification, correspond to modelled object.

CAD model is often sophisticated geometrically, therefore, in order to perform calculations using finite element method, it is idealized which helps to simplify its geometry and eliminate elements that do not affect calculations and to exchange thin panes of model to surfaces, etc. Idealization of a model takes place in order to simplify the task and make the model able to mesh as well as to shorten calculation time.

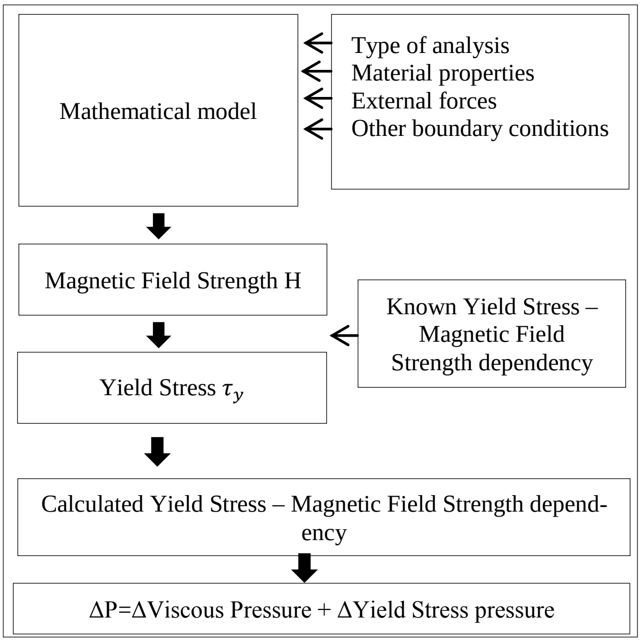



Fig. 1 Algorithm of evaluation of liquid additional pressure from magnetic field influence, which is caused by current in the solenoid

From magneto-rheological fluids documentation that provides Yield Stress – Magnetic Field Strength dependencies, we can calculate yield stress values in accordance to calculated magnetic field strength. Achieved values can be used for calculation of total pressure drop in a system.

## 3. The goal of the research

The main goal of an executed theoretical research is to determine pressure fluctuation change to magneto-rheological fluids in the closed volume under influence of external magnetic field, thus causing fluid chamber to change their shape and deliver displacement to the system. In order to reach the goal, the following tasks have been set: to determine how external magnetic field influences general magneto-rheological fluid‘s pressure fluctuation; to determine parameters that define magneto-rheological fluid's property to change its state when exposed to a magnetic field.

## 4. Research methodology

The pressure drop developed in a device based on pressure driven flow mode is commonly assumed to result from the sum of a viscous component $\Delta P_\eta$ and a field dependent induced yield stress component $\Delta P_\tau$, and can by approximated by [7]:

$$\Delta P = \Delta P_\eta + \Delta P_\tau H = \frac{12\eta QL}{g^3 w} + \frac{c\tau_y(H)L}{g}, \tag{1}$$

where $L$ is the length, $g$ is the gap between fluid walls, $w$ is the width of the flow channel between the fixed poles, $Q$ is the volumetric flow rate, $\eta$ is the viscosity with no applied field, $\tau_y$ is the yield stress developed in response to an applied field $H$. The parameter c is a function of the flow velocity profile and has a value ranging from 2 (for $\Delta P_\eta / \Delta P_\tau$ less than ~1) to a maximum value of 3 (for $\Delta P_\eta / \Delta P_\tau$ less than ~100) [8].

Behavior of controllable fluids is often represented as a Bingham plastic having variable yield strength [7]:

$$\tau_{total} = \tau_y(H) + \eta_p \dot{\gamma}, \tag{2}$$

where $\tau_{total}$ is the total yield stress, $\tau(H)$ is the strength caused by the applied magnetic field $H$, $\eta_p$ is the magnetic field – independent plastic viscosity defined as the slope of the shear stress versus shear strain rate relationship, $\dot{\gamma}$ is the shear rate.

Below the yield stress, material behaves viscoelastically [7]:

$$\tau_{totoal} = G\gamma; \qquad \tau_{totoal} < \tau_y \tag{3}$$

where $G$ is the complex material modulus.

From the formula (1) it is evident, that in order to determine how external magnetic field influences magneto-rheological fluid's pressure loss, it is needed to determine yield stress $\tau_y$. In majority of magneto-rheological fluid's paperwork there is graphs presenting yield stress vs. magnetic field strength, therefore, once magneto-rheological fluid's magnetic field strength is calculated, yield stress figures are available.

To determine magneto-rheological fluid's and Magnetic field Strength (*H*) a Femm 4.2 program was used. The program enables solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains [9].

Femm 4.2 program has three modules:

1. Femm.exe program is designed for creation of geometry, defining of physical properties of materials and boundary conditions of model;
2. Triangle.exe program splits the analysed mathematical model into triangle elements;
3. Fkern.exe is a solver that solves differential equations in order to obtain a solution.

In magnetostatic problems time is invariant, therefore [9]:

$$\nabla \times H = J; \tag{4}$$

$$\nabla \times B = 0, \tag{5}$$

where $H$ is field intensity, $J$ is divergence, $B$ is flux density.

Connection between $B$ and $H$ in each material is expressed as follows [9]:

$$B = \mu H, \tag{6}$$

where $\mu$ is permeability.

For nonlinear materials, the permeability is function of $B$ [9]:

$$\mu = \frac{B}{H(B)}. \tag{7}$$

Femm goes about finding a field that satisfies (4) and (6) via magnetic vector potential approach. Flux density is written in terms of the vector potential, $A$, as [9]:

$$B = \nabla \times A, \tag{8}$$

where $A$ is vector potential.

This definition of $B$ always satisfies (5). The, (4) can be rewritten as:

$$\nabla \times \left( \frac{1}{\mu(B)} \nabla \times A \right) = J. \tag{9}$$

For linear isotropic materials (assuming the Coulomb gauge, $\nabla \times A = 0$), (9) reduces to:

$$-\frac{1}{\mu} \nabla^2 A = J. \tag{10}$$

Femm retains the form (9), so that magnetostatic problems with a nonlinear $B$ - $H$ relationship can be solved.

To execute the research with Femm.exe program there was a two-dimensional solenoid model created and above the solenoid there were MRF fluids situated in an aluminium box.

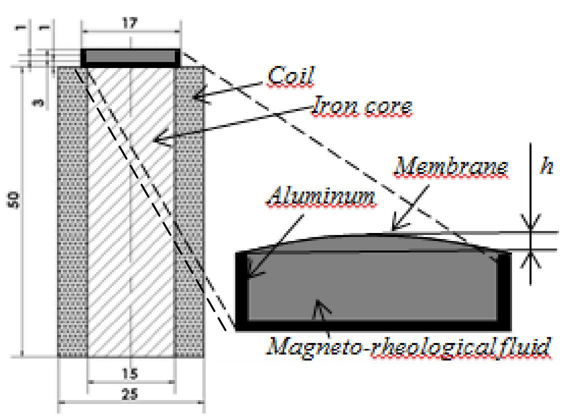
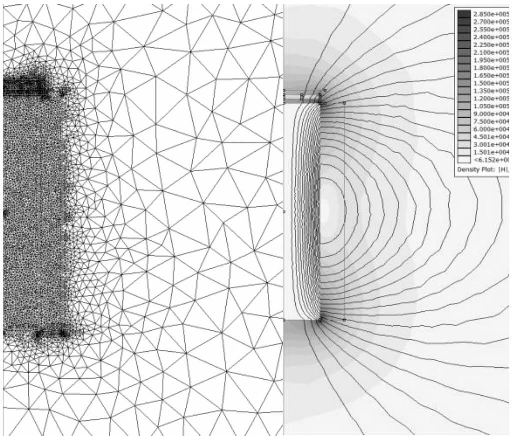



Fig. 2 Principal scheme of solenoid: h - displacement under the influence of magnetic field

Internal height of the box is 1 mm. Magneto-rheological fluid is isolated from external environment by 1 mm aluminium walls. In the research solenoid, MRF and electromagnetic forces were used that were arranged symmetrically and vertically to the axis, therefore the research is axisymmetric meaning that there was a half of the model used for the research. Accurate model dimensions are provided in a Fig. 2. To strengthen magnetic field of solenoid there was an iron core used which had 2000 copper coils of 0.63 mm in diameter winded around iron core.

The analysed model with Triangle.exe program was split into 11852 elements. In total 6133 nodes were generated. Elements number of finite elements mesh was enlarged in those areas, where measures of the model were smaller (Fig. 3).



a b

Fig. 3 Calculation of the magnetic field strength: *a* –meshed solenoid; *b* – density plot of solenoid

In the research there were four Lord Corporation magneto-reological fluids of different characteristics used that are displayed in documentation [10-13].

The research was executed under changing strength of solenoid‘s flow from 0 to 2 A. After each experiment an average magnetic field strength H and magnetic flux density *B*, crossing notional horizontal fluid's symmetry axis was calculated.

After comparing magnetic lines arrangement in Figs. 4 and 5 that are formed under influence of electric streams flowing through solenoid's strands, we can see that magneto-rheological fluids distorts magnetic field's lines of force (Fig. 6).

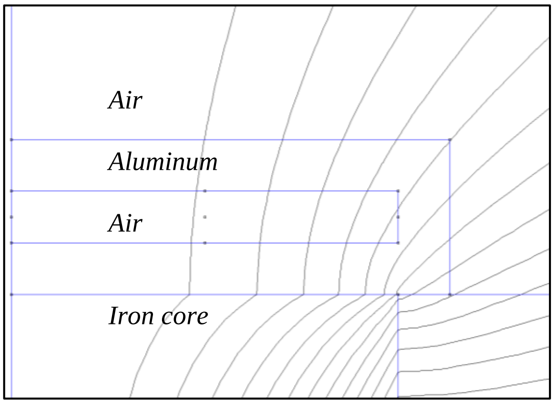



Fig. 4 Simulated magnetic flux lines cross the air

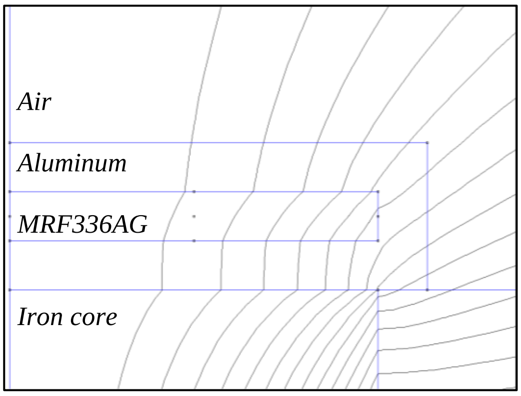



Fig. 5 Simulated magnetic flux lines cross the magneto-rheological fluid MRF-336AG

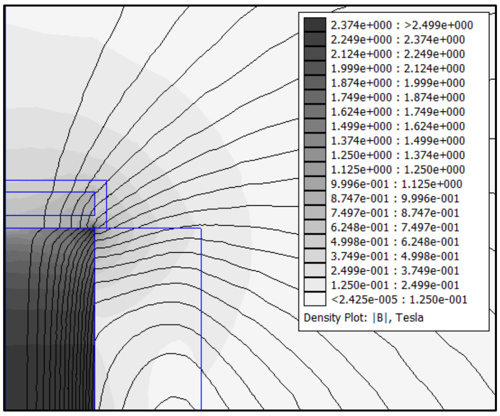



Fig. 6 Simulated magnetic flux density distribution in magneto-rheological fluid MRF-336AG

Generated calculations of magnetic field strength and magnetic flux density figures dependency from strength of the stream flowing through strands of solenoid are presented in Tables 1 and 2 as well as Figs. 7 and 8.

Table 1

Calculated magnetic field strength values of different magneto-rheological fluids

| Current, A | MRF-132AD, kA/m | MRF-140CG, kA/m | MRF-241ES, kA/m | MRF-336AG, kA/m | Air, kA/m |
|---|---|---|---|---|---|
| 0.2 | 2.0 | 1.4 | 1.8 | 1.9 | 3.0 |
| 0.5 | 5.2 | 3.6 | 4.5 | 4.7 | 7.7 |
| 1 | 10.4 | 7.4 | 9.4 | 9.6 | 15.5 |
| 1.5 | 15.6 | 11.3 | 14.8 | 14.9 | 23.2 |
| 2 | 20.9 | 15.7 | 20.8 | 20.6 | 30.9 |

Table 2

Calculated magnetic induction of different magneto-rheological fluids

| Curent, A | MRF-132AD, T | MRF-140CG, T | MRF-241ES, T | MRF-336AG, T | Air, T |
|---|---|---|---|---|---|
| 0.2 | 0.028 | 0.030 | 0.029 | 0.029 | 0.023 |
| 0.5 | 0.071 | 0.074 | 0.073 | 0.072 | 0.055 |
| 1 | 0.142 | 0.148 | 0.144 | 0.144 | 0.11 |
| 1.5 | 0.213 | 0.221 | 0.214 | 0.214 | 0.172 |
| 2 | 0.283 | 0.292 | 0.282 | 0.283 | 0.230 |

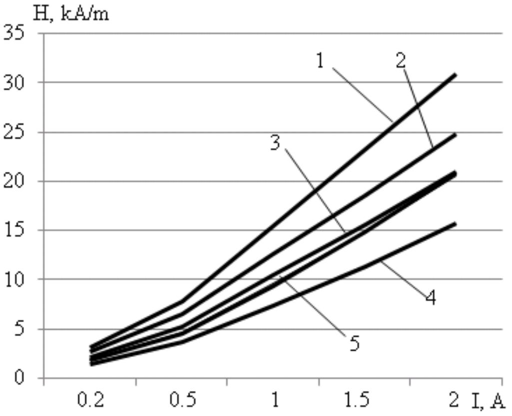



Fig. 7 Calculated magnetic field strength values of different magneto-rheological fluids: *1* – Air; *2* – MRF-132AD; *3* – MRF-336AG; *4* – MRF-140CG; *5* – MRF-241ES

The Fig. 8 shows, that in range of current strength from 0 to 2 A, magnetic induction changes almost linearly.

From researched magneto-rheological fluids documentation that provides Yield Stress – Magnetic Field Strength dependencies, we can take the figures of yield stress in accordance to the figures of magnetic field strength.

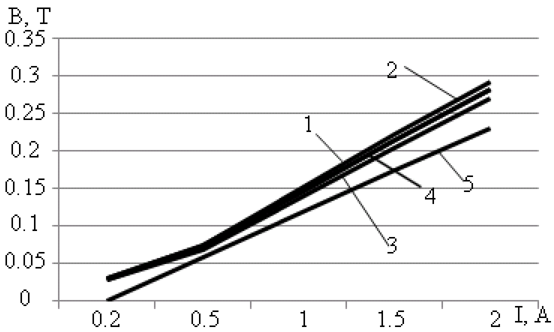



Fig. 8 Calculated magnetic induction of different magneto-rheological fluids: *1* – MRF-132AD; *2* – MRF-140CG; *3* – MRF-241ES; *4* – MRF-336AG; *5* – Air

The results are presented in Table 3 and Fig. 9. Additional pressure generated by magnetic field strength causes change of magneto-rheological fluid surface, therefore the system can be treated as mechanical.

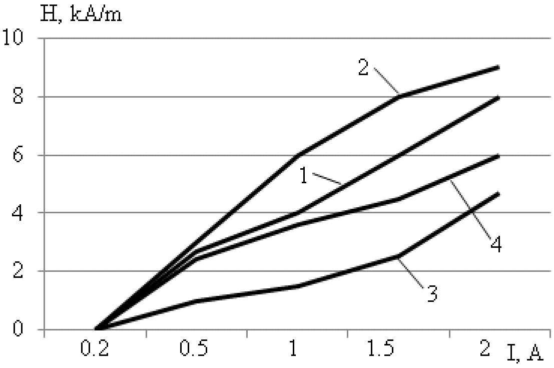



Fig. 9 Calculated Current vs. Yield Stress: *1* – MRF-140CG; *2* – MRF-241ES; *3* – MRF-336AG; *4* – MRF-132AD

Table 3

Current vs. yield stress

| Current, A | MRF-132AD, Pa | MRF-140CG, Pa | MRF-241ES, Pa | MRF-336AG, Pa |
|---|---|---|---|---|
| 0.2 | 0 | 0 | 0 | 0 |
| 0.5 | 2.4 | 2.7 | 3 | 1 |
| 1 | 3.6 | 4 | 6 | 1.5 |
| 1.5 | 4.5 | 6 | 8 | 2.5 |
| 2 | 6 | 8 | 9 | 4.7 |

## 4. Conclusions

After theoretical research of MRF using FEM and modified algorithm of internal pressure definition, some conclusions are made:

1. There is created new methodology, which enables to find mechanical behavior of MRF in magnetic field.
2. Internal pressure from magnetic field in MRF can be obtained for static and dynamic magnetic load case, movement of liquid pressurized membrane requires special CFD analysis.

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TEORINIS MAGNETOREOLOGINIŲ SKYSČIŲ TYRIMAS

R e z i u m ė

Darbe nagrinėjama, kaip keičiasi magnetoreologinių skysčių mechaninės savybės nuolatiniame magnetiniame lauke. Kadangi šių skysčių savybės magnetiniame lauke kinta netiesiškai, tiesiogiai jas išmatuoti sunku. Magnetinio lauko sukuriamas papildomas slėgis keičia magnetoreologinio skysčio paviršiaus padėtį, todėl tokia sistema gali būti laikoma mechanine. Darbe pateiktas algoritmas, leidžiantis nustatyti papildomą slėgį, atsirandantį magnetoreologiniame skystyje dėl solenoide tekančios elektros srovės sukurto magnetinio lauko poveikio. Pateikiamas algoritmas ir metodas, kaip baigtinių elementų metodu gautą rezultatą panaudoti papildomam slėgiui rasti. Tyrimo rezultatai rodo skystyje išorinio magnetinio lauko sukeliamo slėgio charakteristikas ir galimybes panaudoti šį skystį mechaninėse sistemose. Pateikti gauti rezultatai ir išvados.

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THEORETICAL RESEARCH OF MECHANICAL BEHAVIOR OF MAGNETO-RHEOLOGICAL FLUID

S u m m a r y

This paper is intended to research of mechanical behaviour of magneto-rheological fluid in magnetic field. This liquid is with highly non-linear properties in magnetic field and their mechanical behaviour cannot be obtained directly. Additional pressure generated by magnetic field strength causes change of magneto-rheological fluid surface, therefore the system can be treated as mechanical. There is presented algorithm of evaluation of researched liquid additional pressure from magnetic field influence, which is caused by current in the solenoid. There is algorithm and method proposed how finite element method can be used to find additional pressure. The results of this solution give understanding of additional pressure characteristics of magneto-rheological fluid and possibility to use it for magnetically driven mechanical drive. Finally, conclusions on results are made.

**Keywords:** magneto-rheological fluids, combined finite element and property graph analysis, magnetic properties, internal pressure.

Received January 03, 2012
Accepted September 05, 2013