Cezary Jędryczka, Poznan University of Technology

Abstract
The paper deals with coupled electromagnetic, hydrodynamic, thermal and mechanical motion phenomena in magnetorheological fluid transducers. The common structures of those devices are presented and discussed. The governing equations of coupled phenomena are presented. The numerical implementation of the mathematical model is based on the finite element method and a step-by-step algorithm. Selected results of the simulations are presented.

1. Introduction
The viscosity magnetorheological fluids (MRF) depend on magnetic field. Owing to this phenomenon MRF’s can be used for the efficient control of the transmission of torques and forces in so called MRF transducers. The new generation of magnetorheological fluids offers a wide range of applicability in fluid mechatronics with MRF devices such as controllable clutches or brakes. They are used, among others, in rotary brakes, clutches, and rotary and linear dampers [7, 8, 10]. The working principle of electromagnetic transducers with MRF is based on the phenomenon that viscosity changes when the fluid is exposed to a magnetic field. The fluid’s viscosity and the stresses within it increase with the growth of the field. Higher stresses result in increasing forces counteracting the motion of moveable parts in the transducers. The research on magnetorheological (MR) actuators is focused on the analysis of operating states of existing devices and on the methods of improving their functional parameters. Parallel the new designs are also under constant and intensive development [1, 5, 8, 10]. This paper is an attempt to elaborate a method of analysis of coupled phenomena in MR transducers. The focus is on electromagnetic, hydrodynamic, thermal phenomena in respect to the dynamics of moveable elements. The actuators with axial symmetry are considered.

2. Structures of magnetorheological transducers
According to Carlson’s proposal [1, 8], virtually all devices that use MR fluids can be classified as having either: (a) a flow mode (valve mode); (b) a direct shear mode (clutch mode); (c) a squeeze film compression mode; or (d) a combination of these modes. In this paper only the a) and b) devices are considered. A main application area for MRF is in devices for torque transmission which include brakes and clutches. The typical geometries of direct shear mode transducers (controllable brakes and clutches) are presented in Figs. 1 to 4. To simplify in all figures the MRF is marked as a dark grey color. Figure 1 shows a schematic of an MR based disk-type clutches (or brakes, if the outer rotor - housing is not allowed to rotate). Second basic geometries are cylinder shape clutches/brakes (Fig. 2).

Fig. 1. Structure of disk shape clutch with a) rotary coil, b) non rotary coil

Fig. 2. Structure of cylinder shape clutch with winding in outer a) and inner b) rotor

Typically cylinder shape devices have lower moment of inertia comparing to disk shape transducers. In order to increase transmitted torque or power density the drum geometries (Fig. 3) are used.

Fig. 3. Structures of drum shape clutches a) single section; b) double section
The fourth group of basic geometries of MRF brakes or clutches are so called multi-gap solutions. In such devices the active area (where the MR fluid is sheared) is increased by number of fluid gaps and results in increasing clutching or breaking torque of the device. There are two major types of multi-gap geometries: multi plate and multi drum shown in Figs. 4 a) and b) respectively. The disadvantage of multi-gap devices is increase the frictional torque in no current state (when the excitation winding is switched off).

As the examples of direct shear mode devices the disk shape electromagnetic MR clutch and magnetorheological brake with hybrid excitation are presented in Figs. 5 a) and b) respectively. Those transducers were designed, built and tested recent years at Poznan University of Technology (PUT) [5, 6, 7, 9, 10].

Second considered in the paper mode of using properties of MRF in magnetorheological transducers is the valve mode. In this kind devices the fluid flow (caused by external force or torque) can be controlled by the viscosity change that correspond to the current in excitation winding. This mode is used mostly in MR controllable dampers and also in hydrokinetic clutches [7]. The basic geometries of magnetorheological dampers are presented in Figs. 6 and 7. According to MR valve position the two types of MR dampers can be classified: geometries with valve inside and outside the damper chamber (Fig. 6 and Fig. 7, respectively). Dampers with external valve are commonly called a “bypass” type. According to limited area of the fluid gap (valve gap) to achieve higher values of the controlled damping force the multi section solutions are often applied [10]. The multi section solutions for inner and outer valve placement are presented in Figs. 6 b) and 7 b) respectively.

3. Coupled phenomena model and FE formulation

The coupled phenomena models in MR brake, clutch and damper are presented among others in [2, 3, 4]. In these actuators, the velocity field of the fluid depends on the velocity of the moveable parts and distribution of the yield stress in the fluid. This stress is a function of the magnetic field distribution. Forces associated with this stress counteract the motion of the moveable elements of actuator. The total torque is a result of the yield stress in the fluid as well as the electromagnetic forces acting on the moveable elements. Therefore, the velocity field of the fluid, the mechanic stress field and the velocities of moveable parts are coupled with the
electromagnetic field. Moreover, the magnetic permeability $\mu$, the conductivity $\gamma$ of the region with eddy currents, the resistances of the windings and the yield stress of the fluid are functions of the temperature. From the other side, the sources of the heat depend on currents in the windings, eddy current distribution, viscosity of liquid and velocity field. The fields coupling makes the analysis of the phenomena in MR transducers highly complicated. What renders it even more intricate, is the changing character of those fields and the nonlinear character of the equations describing them [2, 4, 7, 10].

In order to solve coupled equations, the FEM and a step-by-step procedure were used [3, 7]. The finite element and time discretisation lead to the following system of nonlinear algebraic matrix equations describing the distribution of the magnetic field, currents in the windings, velocity field and temperatures, respectively [3, 7, 10]

$$\begin{pmatrix} S_n + \Delta t^{-1} G - N \end{pmatrix} \begin{bmatrix} \varphi_n \\ i_n \end{bmatrix} = \begin{bmatrix} 0_n + \Delta t^{-1} G \varphi_{n-1} \\ -\Delta t \theta_n - N^{T} \varphi_{n-1} \end{bmatrix},$$

(1)

$$[F_n + \Delta t^{-1} M] \phi_n = \Delta t^{-1} M \phi_{n-1},$$

(2)

$$[T_n + \Delta t^{-1} K] \Theta_n = \Delta t^{-1} K \Theta_{n-1} + P,$$

(3)

where $n$ denotes present time-step number, $\Delta t$ is the time step length, $S$, $F$, $T$ are the magnetic, fluid dynamic and thermal stiffness matrices, respectively, $\phi$, $\varphi$ and $\Theta$ are the vectors of the nodal potentials $\phi$, $\varphi$ and $\Theta$ respectively, $N$ is the matrix that transforms the potentials $\varphi$ into flux linkages with the windings, $\theta$ is the vector of magnetomotive forces in regions with currents, $G$ is the matrix of conductances of elementary rings formed by the mesh, $M$ is the matrix with elements determined by the dimensions of the elementary rings and the fluid density $\rho$, $K$ is diagonal matrix of elementary rings heat capacity and vector $P$ describes the heat sources in the considered transducer.

In the MR transducers the heat sources are related to Joule’s losses in windings and regions where eddy current appears and losses related to internal friction of the MR fluid. The elements of the heat sources vector $P$ are described by discrete values of power loss density $P_0$ which can be described as follows

$$P_0 = \begin{cases} P_{0J} = J^2 / \gamma, & \text{for regions with currents} \\ P_{0MRF} = \xi |\bar{D}|, & \text{for regions with MRF} \end{cases},$$

where $J$ is the current density, $\xi$ is the equivalent fluid viscosity obtained from Bingham model and $D$ is the velocity deformation tensor.

Presented above field equations (eqs. 1 to 3) must be solved together with mechanical equilibrium equations of movable parts of the considered transducer. Those equations are different for brakes, clutches and dampers and depend also on dynamic of the load and drive systems. Therefore in this broadly defined formulation those equations will be omitted. Information how to introduce the dynamic equations have been present in the papers focused on particular devices ie. [5, 6, 9].

The above equations are nonlinear and coupled. In order to solve these equations the block relaxation procedure was used. Due to high nonlinearity of considered problem to solve obtained matrix equations systems the iterative Newton-Raphson was used.

4. Results of simulations

To prove elaborated model accuracy and functionality of developed software the selected results of steady and transient states simulations are presented. Simulations have been performed for chosen transducers working in direct shear mode. Figures 9 and 10 shows the meshes of analyzed electromagnetic disk shape MR clutch and magnetorheological brake with hybrid excitation, respectively. Meshes where quite dense, the considered regions where subdivided into 79 690 and about 90 000 finite elements for the clutch and the brake respectively.

Fig. 9. Mesh of electromagnetic disk shape MR clutch – from Fig. 5 a)

Fig. 10. Magnetorheological brake with hybrid excitation – from Fig. 5 b)

As a sample problem the transient state after switching on and off supply voltage for excitation coil of the MR disk shape clutch has been analysed.
Obtained, for chosen time instants, the magnetic flux lines distributions are presented in Fig. 11.

![Fig. 11. Flux lines distributions for chosen time instants in disk shape MR clutch](image)

It can be observed that the eddy currents have significant impact on reaction time of considered device.

![Fig. 12. Flux lines distributions for active and passive operation mode of the considered MR brake](image)

As a second sample problem the steady state operation of MR brake with hybrid excitation has been analyzed. The magnetic field distributions for excited state (current in the windings) and passive state (no current in the windings) are shown in Figs. 12 a) and b), respectively.

Detailed results of analysis of considered MR transducers, as well as results of measurements of built at PUT their prototypes can be found in [7, 10].

**5. Conclusions**

Presented model, elaborated algorithm and developed software have been successfully used to the analysis of the transient coupled fields in the MR actuators. The achieved good concordance between the calculations and measurements [6, 7, 9, 10] proves the accuracy applied model. Therefore in author opinion elaborated algorithm and software can be used as effective tool in the analysis of the steady state and the transients in MRF devices.

**Bibliography**


**Author:**

PhD Cezary Jędryczka
Poznan University of Technology
ul. Piotrowo 3a
60-965 Poznan
tel. (061) 647 58 03
fax (061) 665 23 81
email: cezary.jedryczka@put.poznan.pl