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MAGNETORHEOLOGICAL ROTARY-LINEAR BRAKE – ANALYSIS OF MAGNETIC FIELD DISTRIBUTION AND FORCES AT STANDSTILL

ABSTRACT *The magnetorheological fluid is a magnetic one. A magnetic fluid changes its properties (viscosity) under the influence of an external magnetic field. The consistence of the fluid changes in a magnetic field: from a dense fluid being a suspension of ferromagnetic particles in the carrier fluid (Fig.1a) it becomes a hard mass, like frozen butter. This effect is the result of changes in the fluid structure: the ferromagnetic particles of the fluid, being single domains, when subjected to an external magnetic field, become orientated and concentrated along the lines of forces of the magnetic field (Fig.1b). In stillstand the fluid behaves like an elastic body, as long as the tangential stresses in the body do not exceed the limit values* $\tau_0(B)$.

The magnetorheological fluid found applications first of all in brakes and dampers. The design of the electromechanical converters mentioned above permits the space between the casing and the moving component of the converter to be filled with the magnetorheological fluid. A coil supplied with power is placed on the moving component of the converter or inside the casing, depending

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on the design type. The current flowing through coil produces a magnetic flux which penetrates the layer of fluid between the casing and the moving element of the converter. A change in the force of resistance to motion results from the change in the fluid viscosity which is obtained by the control effected with the magnetic field (current flowing through the coil).

The essence of the design of the rotary-linear brake (Fig.3) is the integration in a single piece of equipment the magnetorheological rotary brake and a magnetoreological linear brake. The magnetorheological rotary-linear brake permits to obtain change in the torque in the rotary movement, and in the braking force in the linear movement, as well as in the torque and the braking force in a composed rotary-linear movement.

The created 3-dimensional field model of the brake (Fig.4) (constituting a quarter of the brake, because of its biplanar symmetry) permits the magnetic field distribution in the brake to be determined. The determined magnetic field distributions: at the linear brake coil (Fig.5a) and the rotary brake coil (Fig.5b) supplied with power, permit the maximum linear braking force F *(Fig.6a) to be determined from* $\tau_0(B(x, y, z))$, *and the maximum braking torque* T *(Fig.6b), produced by the brake in stillstand. The results obtained, show that the forces* (F) *and torques* (T) *produced by the brake can be easily controlled.*

1. INTRODUCTION

Magnetorheological fluids are one of two kinds of magnetic fluids, which were discovered by J. Rabinow in half of XX century. Magnetic fluids are used in different domains of technique, particularly in electromechanical devices. Thanks to magnetic fluid's properties devices with this fluid enable to change the parameters of a mechanic system (rigidity, braking force) as a result of electric voltage and current control. It is worth to mention that this control is simple, doesn't require complicated and energy-consuming control systems. This fact is undoubtedly an advantage of devices applying magnetic fluid as well as systems which employ these devices – mechatronic systems.

2. STRUCTURE OF THE MAGNETIC FLUIDS AND THEIR BASIC PROPERTIES

Magnetic fluid is suspension of ferromagnetic particles in a carrier liquid (Fig.1a). In the external magnetic field the magnetic fluid changes its proprieties:

consistency is changing from thick liquid to solid. This effect results from change of fluid's structure: the ferromagnetic particles acquire a dipole moment aligned with the external field which causes particles to form linear chains parallel to the field (Fig.1b) After disappearance of the external magnetic field magnetic fluid regains its initial properties: the ferromagnetic particles because of nonmagnetic layer (Fig.1a) don't get stuck together but disperse as results of thermal motion (disperse time about single microsecond). If the magnetic fluid is located in non-homogeneous magnetic field, ferromagnetic particles move to stronger magnetic field region (Fig.1c). The stronger magnetic field the larger stresses of linear chains of ferromagnetic particles – the viscosity increases. In consequence of this fact it exists a possibility to control the fluid's viscosity using the magnetic field.

a) b) c)

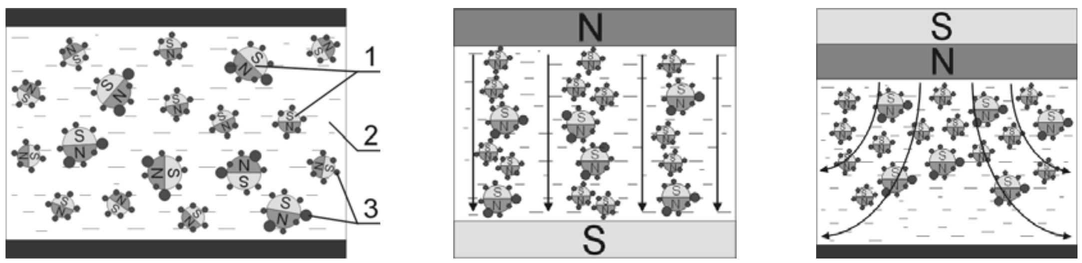


Fig.1. Magnetic fluid:

a) structure of the fluid: 1 – ferromagnetic particles, 2 – carrier fluid, 3 – nonmagnetic layer, b) in external homogenous magnetic field, c) in external non-homogenous magnetic field

A change of the viscosity of the magnetic fluid is described by the Bingham law [3] (Fig.2)

$$\tau = \tau_0(B) + \mu\dot{\gamma} \tag{1}$$

where:

τ – shear stress,
$\tau_0(B)$ – yield stress caused by the applied field,
μ – plastic viscosity,
$\dot{\gamma}$ – shear strain rate.

If $\tau < \tau_0(H)$ the magnetic fluid behaves like an elastic body (standstill state).

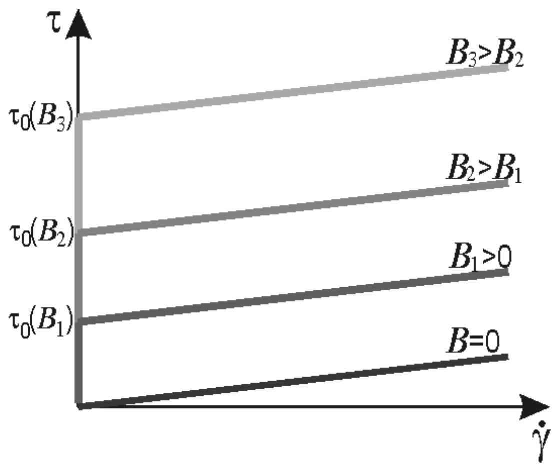


Fig.2. The feature of the magnetic fluid described by the Bingham's law

For the sake of construction and properties of magnetic fluid one can distinguish two kinds of them [1, 3]:

- ferrofluids, with the following properties:
  - suspension of ferromagnetic participles in carrier liquid,
  - diameter of participles is about 10 nm,
  - percentage content of ferromagnetic materials: about (2-15) %,
  - maximum shear stress: about 10 kPa,

- magnetorheological fluids (MRF), with the following properties:
  - colloidal suspension of ferromagnetic participles in carrier liquid,
  - diameter of participles: (5-10) μm,
  - percentage content of ferromagnetic materials: (20-85) %,
  - maximum shear stress: about 250 kPa.

Comparing both kinds of magnetic fluid, it is necessary to mention that production of magnetorheological fluid is considerably cheaper and easier than the production of ferrofluid [1].

3. MAGNETORHEOLOGICAL DEVICES

The differences in properties of ferrofluid and magnetorheological fluid lead to various application of the fluid for different types of devices. Magnetorheological fluid is used first of all in brakes (rotary brakes) and dampers (linear brakes), because it is possibility to obtainment large shear stresses in fluid. Constructions of these electromechanical devices (brakes and dampers) enable to introduce magnetorheological fluid in space between casing and moving element. In the brake the moving element is rotor and in the damper is piston. This electromechanical device includes an electric coil. The coil is placed in the casing or on the moving element – it depends on type of device. A current flow in the coil determines braking force: the current flowing in the coil generates magnetic field, which pervades the layer of magnetorheological fluid between casing and moving element and changes viscosity of this part of the magnetorheological fluid. The change of the viscosity is the reason for changing braking force.

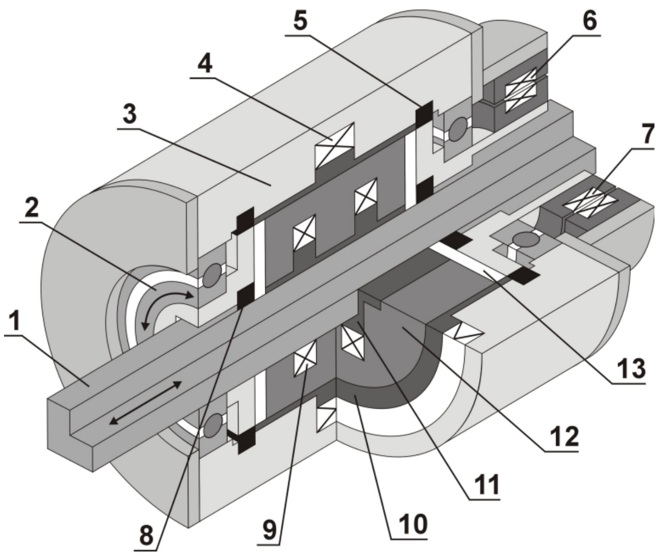


Fig.3. Magnetorheological rotary-linear brake:

1 - shaft, 2 – bearing, 3 – housing of the rotary brake (ferromagnetic core), 4 – rotary brake's coil, 5 – seal of the rotary brake, 6 - primary windings of the rotary transformer supplying coils of the linear brake, 7 - secondary of the rotary transformer supplying coils of the linear brake, 8 - seal of the linear, 9 - linear brake's coil, 10,11 – magnetorheological fluid, 12 - housing of the linear brake (ferromagnetic core), 13 – shift's ways

4. MAGNETORHEOLOGICAL ROTARY-LINEAR BRAKE

The conception of rotary-linear brake with magnetorheological fluid (Fig.3) was created on the basis of researches of a magnetorheological linear damper and a magnetorheological rotary brake [2]. The magnetorheological rotary-linear brake consists of two modules (brakes):

- rotary module (rotary brake) – its construction is similar to magnetorheological rotary brakes with cylindrical rotor and coil placed in the housing; the rotor is a housing of the linear brake;
- linear module (linear brake) – its construction is an atypical, and arises from dissection and linear development of magnetorheological rotary brake construction; the magnetorheological linear brake has rectangular shaft which enables transmission of rotary torque to the linear brake's housing – rotary brake's rotor; two coils are placed in linear brake's housing on two opposite shaft's sides; by the others shaft's sides are placed two drains compensating differential pressure, which is generated by shaft's movement.

The rotary brake's coil is directly supplied from DC source. The linear brake's coil must be supplied from AC source through a rotary transformer and a rectifier.

Magnetorheological rotary-linear brake enables change of braking torque in rotary motion as well as braking force in linear motion. This fact enables using magnetorheological rotary-linear brake as the rotary brake in rotary power transmission system or as the linear brake in linear power transmission system or else as rotary-linear brake in complex power transmission systems.

5. MAGNETIC FIELD MODEL OF THE MAGNETORHEOLOGICAL ROTARY-LINEAR BRAKE

The magnetorheological rotary-linear brake has two symmetry planes - xz plane and yz plane. For this reason 3D magnetic field model of the brake can be only a quarter of the brake (Fig.4).

The magnetic field model allows for non-linear magnetization curves of steel [6] and magnetorheological fluid [4]. Magnetic field distribution was calculated for two cases – for rotary brake's coil supplying and by rotary brake's coil supplying – for different current densities of coils J. The results of calculation for selected current densities of coil are shown on Fig.5.

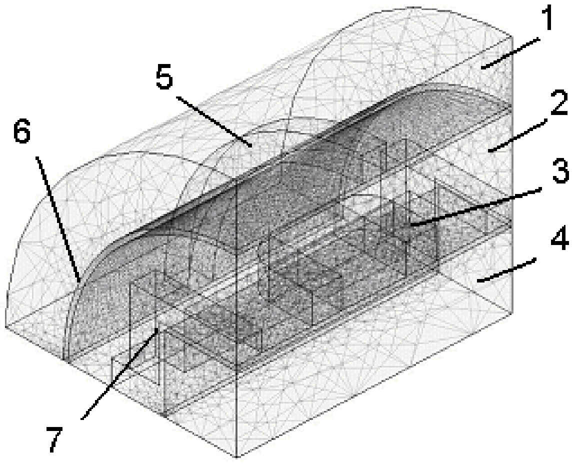
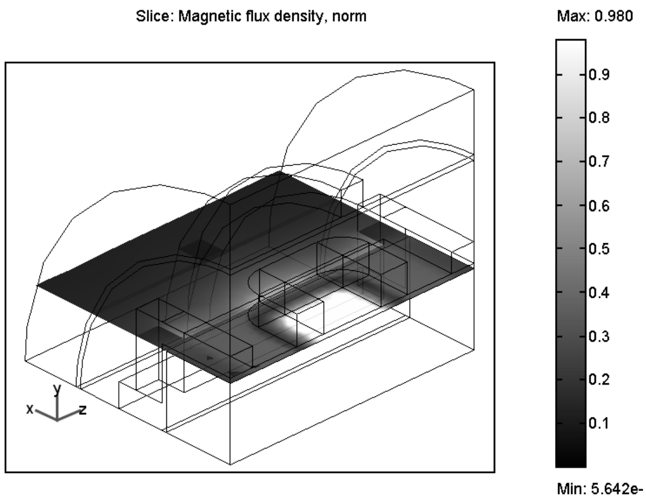


Fig.4. 3D magnetic field model of magnetorheological rotary-linear brake :
1 – housing of the rotary brake (steel), 2 – housing of the linear brake (steel), 3 – linear brake's coil, 4 – shaft (steel), 5 – rotary brake's coil, 6 – magnetorheological fluid of rotary brake, 7 – magnetorheological fluid of linear brake

a)



b)

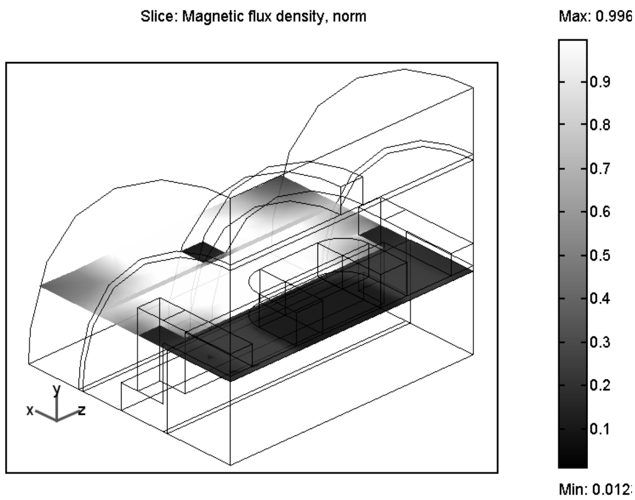


Fig.5. Magnetic field distribution in magnetorheological rotary-linear brake:
a) for linear brake's coil supplying, b) for rotary brake's coil supplying

6. CALCULATION OF FORCES AT STANDSTILL

Maximum braking forces (linear force and rotary torque) at standstill, produced by the magnetorheological rotary-linear brake can be calculated from magnetic field density distribution $B(x, y, z)$ and yield stress of magnetorheological fluid $\tau_0(B)$ [4]. Fig.6 shows the results of calculation from surface integration [5] of $\tau_0(B(x, y, z))$ on boundary of:

- the magnetorheological fluid of linear brake and the shaft (for linear brake's supply) (Fig.6a),
- the magnetorheological fluid of rotary brake and the rotor (for rotary brake's supply) (Fig.6b).

a) b)

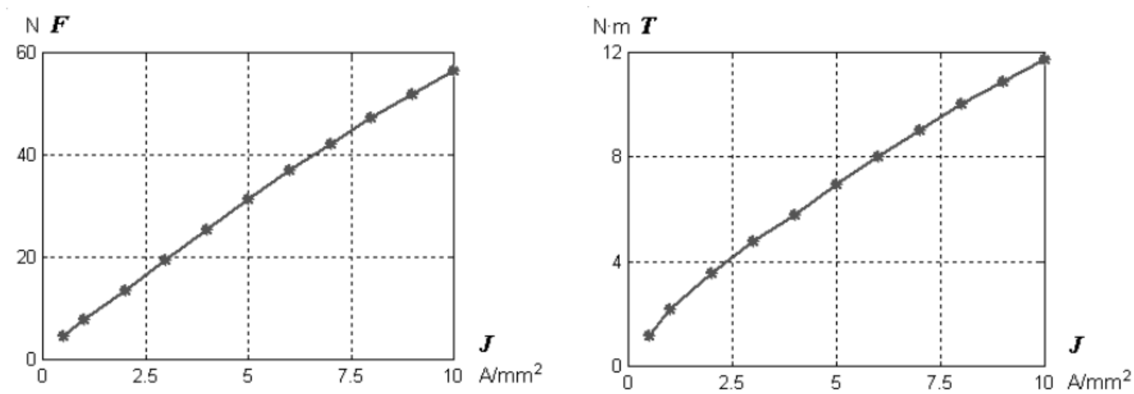


Fig.6. Maximum braking forces produced by the magnetorheological rotary-linear brake at standstill: a) linear braking force F versus current density J of linear brake's coil, b) rotary braking torque T versus current density J of rotary brake's coil

7. CONCLUSIONS

The magnetic field distributions (Fig.5) and the results of force calculations (Fig.6) show that it is possible to construct the brake with magnetorheological fluid which produces braking forces in two different directions. The maximum braking forces (braking linear force and braking rotary torque) at standstill are easy to control by current of brake's coils. The presented results of researches are the first part of magnetorheological rotary-linear brake's field calculations. Future researches will be aimed at: evaluation of mutual influence of the rotary and linear brakes (modules) at standstill and study of coupled magnetic and hydrodynamic fields at movement.

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MAGNETOREOLOGICZNY HAMULEC OBROTOWO-LINIOWY – OBLICZENIA ROZKŁADU POLA MAGNETYCZNEGO I SIŁ W STANIE BEZRUCHU

Paweł KOWOL

STRESZCZENIE *Ciecz magnetoreologiczna jest cieczą magnetyczną. Ciecz magnetyczna zmienia swoje właściwości (lepkość) pod wpływem zewnętrznego pola magnetycznego. W polu magnetycznym konsystencja cieczy ulega zmianie: z gęstej cieczy, będącej zawiesiną drobinek ferromagnetyka w cieczy nośnej (rys.1a), staje się twardą masą niczym zmarznięte masło. Efekt ten wynika ze zmiany struktury cieczy: ferromagnetyczne cząsteczki cieczy, będące pojedynczymi domenami, pod wpływem zewnętrznego pola magnety-*

cznego ulegają orientacji i koncentracji wzdłuż linii sił pola magnetycznego (rys.1b). Zmianę lepkości cieczy magnetycznej opisuje prawo Binghama (1) (rys.2) [1, 3]. W stanie bezruchu, jeśli naprężenia styczne w cieczy nie przekroczą naprężeń granicznych $\tau_0(B)$ – – ciecz zachowuje się jak ciało sprężyste.

Ciecz magnetoreologiczna znalazła zastosowania przede wszystkim w hamulcach i tłumikach. Konstrukcja wspomnianych przetworników elektromechanicznych umożliwia wypełnienie cieczą magnetoreologiczną przestrzeni pomiędzy obudową a elementem ruchomym przetwornika. Na elemencie ruchomym przetwornika bądź w odbudowie – w zależności od typu konstrukcji – umieszcza się cewkę zasilaną prądem. Prąd przepływający przez cewkę wytwarza strumień magnetyczny przenikający przez warstwę cieczy znajdującej się pomiędzy obudową a elementem ruchomym przetwornika. Zmiana siły oporu ruchu wynika ze zmiany lepkości cieczy, którą uzyskuje się poprzez sterowanie polem magnetycznym (prądem przepływającym przez cewkę).

Istotą konstrukcji magnetoreologicznego hamulca obrotowo-liniowego (rys.3) jest zintegrowanie w jednym urządzeniu magnetoreologicznego hamulca obrotowego i magnetoreologicznego hamulca liniowego. Magnetoreologiczny hamulec obrotowo-liniowy umożliwia zmianę zarówno momentu hamującego w ruchu obrotowym, siły hamującej w ruchu liniowym, jak i momentu hamującego i siły hamującej w złożonym ruchu obrotowo-liniowym.

Stworzony trójwymiarowy model polowy hamulca (rys.4) (stanowiący jedną czwartą hamulca – ze względu na jego dwupłaszczyznową symetrię) pozwala na wyznaczenie rozkładu pola magnetycznego w hamulcu. Wyznaczone rozkłady pola magnetycznego: przy zasilaniu cewki hamulca liniowego (rys.5a) oraz przy zasilaniu cewki hamulca obrotowego (rys.5b), pozwalają na wyznaczenie – z $\tau_0(B(x, y, z))$ – maksymalnej liniowej siły hamującej F (rys. 6a) i maksymalnego momentu hamującego T (rys.6b), wytwarzanych przez hamulec w stanie bezruchu. Otrzymane wyniki wykazują łatwość sterowania siłami (F, T) wytwarzanymi przez hamulec.