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Analysis of Magnetorheological Fluid Brake System and its Operation

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ABSTRACT

The MR brake consists of multiple rotating disks immersed into an MR fluid and an enclosed electromagnet. When current is applied to the electromagnet coil, the MR fluid solidifies as its yield stress varies as a function of the magnetic field applied by the electromagnet. This controllable yield stress produces shear friction on the rotating disks, generating the braking torque. This type of braking system has the following advantages: faster response, easy implementation of a new controller or existing controllers (e.g. ABS, VSC, EPB, etc.), less maintenance requirements since there is no material wear and lighter overall weight since it does not require the auxiliary components used in CHBs. The MRB design process included several critical design steps such as the magnetic circuit design and material selection as well as other practical considerations such as cooling and sealing. A basic MRB configuration was selected among possible candidates and a detailed design was obtained according to a set of design criteria. Then, with the help of a finite element model (FEM) of the MRB design, the magnetic field intensity distribution within the brake was simulated and the results were used to calculate the braking torque generation.

Keywords : MRB, MRF, Electromechanical brakes , finite element model , ABS, VSC, EPB

I. INTRODUCTION

The conventional friction brake (FB) is the most commonly used brake type in almost any mechanical system today. However, it is characterized by drawbacks such as periodic replacement due to wear, large mechanical time-delay, bulky size etc. partially altered. Electromechanical brakes (EMBs) have potential to overcome some of these drawbacks and are a suitable FB replacement. Today EMBs are applicable in almost any mechanical system.

In this thesis work, an EMB based on magnetorheological fluids (MR fluid or MRF), i.e. a magnetorheological brake (MRB), is presented. MRB is a friction based brake like a CHB. However, the method of the friction generation in an MRB is entirely different. In the CHB, when the braking pressure is applied, the stator and rotor surfaces come together and friction is generated between the two surfaces, resulting in the generation of the braking torque. But in the MRB, MRF is filled between the stator and the rotor, and due to controllable rheological characteristics of the MRF, shear friction is generated (thus the braking torque).

Application of intelligent materials is the next step in the development of EMB.

Magnetorheological (MR) fluids belong to a class of intelligent materials that respond to applied magnetic field with fast, continuous, and reversible change in its rheological behaviour partially altered. It Consist micron (1-10 μm) sized, magnetically polarizable (soft magnets) dispersed in a carrier liquid such as mineral, silicone oils, kerosene, water .When exposed to external magnetic field particles form a chain-like structures thus changing the viscosity of the fluid. It Makes device smart by changing system's properties(stiffness, damping, viscosity, shear modulus) in a desirable manner. It is useful in active control of vibration & motion, i.e. engine mount, shock absorbers, seat dampers, variable resistance equipment, etc. Motion damping is perhaps the most practical use for MR technology today. It is 20-50 times stronger than ER fluids, lower sensitivity to impurities. The practical necessities often require attenuation of the vibrations which comes under passive damper, active damper, semi-active damper

Most devices that use MR fluids can be classified as having:

– Fixed poles (Pressure driven flow mode)

- Servo-valves, dampers and shock absorbers

– Relatively moveable poles (Direct-shear/sliding mode).

- Clutches, brakes, chucking and locking devices.

MR fluids are suspensions composed out of three major components: carrier fluid - usually mineral or synthetic oil, magnetizable particles - carbonyl iron powder and set of additives, partially altered. When exposed to an external magnetic field (ON state), change in MR fluid's viscosity occurs. In the absence of an external magnetic field (OFF state), MR fluid acts as Newtonian fluid and can be described as:

$$\zeta = \eta \cdot \dot{Y} \qquad \text{... (1)}$$

In (1) ζ represents shear stress, η the viscosity of the fluid and $\dot{Y}$ shear rate. Often, for MR fluid brakes, denoted as

$$\dot{Y} = r \cdot \omega / g,$$

where r is rotor radius, ω and g are angular speed and MR fluid gap length, respectively.

When in ON state MR, the rheological properties of MR fluid change. Magnetizable particles induce polarization and form chain-like structures in magnetic flux path direction, thus changing apparent viscosity of the fluid. ON state behaviour of MR fluid is often represented as a non-Newtonian having a variable yield strength. The usage of Bingham's model (2), in this situation, gives reasonably good results,

$$\zeta = \zeta B + \eta \cdot \dot{Y}, \qquad \text{... (2)}$$

where ζB is the yield stress developed in response to the applied magnetic field. Its value is a function of the magnetic field induction B. When used in a device, MR fluid can be in one of four modes: shear, flow (pressure), squeeze and pinch. In brake i.e. torque transfer applications, MR fluid operates in shear mode, braking torque values are adjusted continuously by changing the external magnetic field strength.

MR brake consists out of four main parts: rotor, housing i.e. stator, coil and MR fluid, One needs the quantitative parameters of MR brake, to be able to determine its specific application suitability.MR brake types, mechanical model, quantitative parameters comparison for all MR brake types are presented in next section. The MR brake consists of multiple rotating disks immersed into an MR fluid and an enclosed electromagnet. When current is applied to the electromagnet coil, the MR fluid solidifies as its yield stress varies as a function of the magnetic field applied by the electromagnet. This controllable yield stress produces shear friction on the rotating disks, generating the braking torque. This type of braking system has the following advantages: faster response, easy implementation of a new controller or existing controllers (e.g. ABS, VSC, EPB, etc.), less maintenance requirements since there is no material wear and lighter overall weight since it does not require the auxiliary components used in CHBs.

II. LITERATURE REVIEW

MR fluids have attracted extensive research interest in recent years since they can provide simple, quiet and fast response interface between electronic control and mechanical system.

A lot of work was done on MR fluid brakes modelling, properties investigation and control .A wide range of MR fluid devices have also been investigated for their potential applications in different systems, such as: clutch system, vibration control, seismic response reduction, etc.
MR fluid brakes have also been used in actuators due to their distinguished force control and power transmission features. By applying a proper control effort, viscosity with large varying range is achievable with the MR fluid brake. Currently, there are many solutions for MR fluid brake design. Some MR fluid brakes with attractive properties, such as high yield stress and stable behaviour, have been developed and commercialized.

In their paper "**Design of a Magnetorheological Brake System Based on Magnetic Circuit Optimization**"they proposed that In order to obtain an optimal MRB design with higher braking torque generation capacity and lower weight, the key design parameters were optimized. The optimization procedure also consisted of the FEM, which was required to calculate the braking torque generation in each iteration. Two different optimization search methods were used in obtaining the minimum weight and maximum braking torque: (i) a random search algorithm, simulated annealing, was first used to find an approximate optimum design and (ii) a gradient based algorithm, sequential quadratic programming, was subsequently used to obtain the optimum dimensional design parameters.

In their paper" **Magnetorheological Fluid Brake – Basic Performances Testing With Magnetic Field Efficiency Improvement Proposal"** Based on overall braking torque analytical comparison for all magnetorheological brake types and other relevant parameters, the most promising design was selected. A test rig, utilizing selected brake type filled with magnetorheological fluid – Basonetic 5030 was manufactured and then tested. To analyze the effect produced by magnetic field on magnetorheological fluid and hence at overall braking torque, the authors used amplification factor. Results were discussed and the magnetic field efficiency improvements were proposed.

In their paper" **Theoretical Studies on Magnetorheological Fluid Brake**", the design method of the cylindrical MR fluid brake is investigated theoretically. The mechanical part is modelled using Bingham's equation, an approach to modelling the magnetic circuit is proposed in this work. The equation of the torque transmitted by the MR fluid within the brake is derived to provide the theoretical foundation in the cylindrical design of the brake. Based on this equation, after mathematical manipulation, the calculations of the volume, thickness and width of the annular MR fluid within the cylindrical MR fluids brake are yielded.

In their paper"**Synthesis and characterization of magnetorheological fluids for magnetorheological brake operation**" they proposed to synthesize MR fluid sample which will typically meet the requirements of MR brake applications. In this study, various electrolytic and carbonyl iron powder based MR fluids have been synthesized by mixing grease as a stabilizer, oleic acid as an antifriction additive and gaur gum powder as a surface coating to reduce agglomeration of the MR fluid. MR fluid samples based on sunflower oil, which is bio-degradable, environmentally friendly and abundantly available have also been synthesized. These MR fluid samples are characterized for determination of magnetic, morphological and rheological properties. This study helps identify most suitable localized MR fluid meant for MR brake application

III. PROPOSED WORK

There are some variations in MR disk brake design such as: the use of two coils instead of one in order to increase the magnetic pole area and/or relocation of the coil on top of the disk in order to reduce its external diameter, but the basics remain the same. It is also interesting to note that the MR disk brake design is currently the only one commercially available as a standard product, manufactured by Lord Corporation and that it was used in several studies.

In order to increase compactness of the MR disk brake design, several disk-shape rotors can be used instead of one, with segments of stator located in between each rotor disk, *Fig. 1.e*.

This multiple disk design is very popular in literature and was used in several applications that required high torque in limited space and weight. The equations describing this particular design are very similar to those of the single disk brake, presented paper's sequel.

The T-shape rotor brake design *(Fig. 1.c)*, is more compact than all other designs but is also more complex to manufacture. Despite its advantages, this design is not so common in literature.

For all aforementioned MR brake types, the rotor has a cylindrical shape and the magnetic flux lines run in the radial direction, *Fig. 1*.

The key objective in MR fluid brake design is to establish the relationship between the overall braking torque, magnetic field strength and design parameters. Interaction of MR fluid and inner surfaces of the brake will generate the braking torque. Based on *Eq. (2)* and the specific geometrical configuration of MR brake, for all MR brake types, it applies:

$$dT = 2\pi N \zeta r^2 dr, \quad \ldots (3)$$

where:

N –number of surfaces of the rotor, perpendicular to the magnetic flux lines and in contact with MR fluid,

r – the radius of the rotor.

The overall braking torque $T_{Overall}$, consists of three components:

- the magnetic field induced component T_B, due to the field-dependent yield stress,

- the fluid viscosity dependent component T_{vis} and

- the friction induced component T_{fric}..

Thus, the overall brake torque:

$$T_{Overall} = T_B + T_{vis} + T_{fric}. \quad \ldots (4)$$

The sum of the first two components T_B and T_{vis} i.e. the braking torque can be obtained by the following integral:

$$T_B + T_{vis} = 2\pi N \int_{R_i}^{R_o} \zeta r^2 dr \quad \ldots (5)$$

where R_O and R_i are the brake rotor outer and inner radii respectively. Considering practical conditions, for all MR brake types, the value of the R_i can be ignored because the R_O is several order of magnitude of the R_i.

Based on *Eq. (5)*, the final analytical expressions for all five MR brake designs.

Expressions were adopted from several different literature sources and were partially altered in order to make the comparison easier.

The last part of torque, T_{fric} can be precisely obtained only by torque gauge.

$T_{OVERALL}=\prod((4/3)\zeta R_o^3+ \eta(\omega/g)R_o^4)+ T_{fric}$ ...(6)

$T_{OVERALL}=\prod N((4/3)\zeta R_o^3+ \eta(\omega/g)R_o^4)+ T_{fric}$ ...(7)

$T_{OVERALL}=4\prod h(\zeta R_o^3+ \eta(\omega/g)R_o^3)+ T_{fric}$ ...(8)

$T_{OVERALL}=8\prod h(\zeta R_o^2+ \eta(\omega/g)R_o^3)+ T_{fric}$ ...(9)

Variable h is the height of the rotor.

It is now easy to distinguish components of overall braking torque in *Eq. (6–9)*, for disk, multiple disks, drums and T-shaped rotor, respectively. The yield stress ζ_B given in *Eq. (2)*, varies with magnetic induction, but can reasonably be fitted with the third-order polynomial as follows:

$$\zeta_B=K_1B+K_2B^2+K_3B^3 \quad ...(10)$$

where K_i represents coefficients of regression.

IV. RESULT ANALYSIS

The experiment itself consisted out of three parts.
The first part was to determine the influence of the supporting ball bearings and seals, without MR fluid inside the brake and no control current applied. This was a friction braking torque component.

Second part of the experiment had the same setup but *it included MR fluid inside the brake*. Viscous torque data was then recorded, assuming that bearings and seals did not change their friction characteristics in time.

A fore mentioned recordings were needed in order to get clear and precise information about field induced component. This was the third part of the experiment and it included MR fluid inside the brake and application of the control current.

The same speed sets were used for the friction and the viscous torque component measurements were repeated. Some field induced component results are depict in *Figure 5*. Magnetic field influence is apparent.

Amplification factor (AF) represents relation between overall braking torque and sum of friction and viscous torque, i.e. relation between the ON and OFF state of the MR fluid.

$$AF=\frac{T_{OVERALL}\ \text{at Current I}}{T_{OVERALL}\ \text{at 0 Current}}$$

V. CONCLUSION

Based on this information, the most promising MR brake type can be selected, tested on a specially designed test rig. The MR brake produced desirable results, which coincide with literature sources. Approximately linear relation between the overall braking torque and the control current intensity was observed. To present results in more readable manner, the amplification factor is introduced.

The experiment showed that the MR brake has potential for practical applications due to easiness and accuracy of control. However, the value of the overall braking torque is still small. To increase it, better utilization of the existing magnetic field is needed By multiplying the number of the disks in contact with MR fluid, value of the overall braking torque will multiply as well,. In order to maximize the potential of the proposed MR brake, further investigations on magnetic field propagation is needed as well as design optimization.

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