# Design and Experimental Validation of an MR-Fluid Based Brake for use in Haptics

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**Abstract:**
In this work, the design of an MR-fluid based brake system is given which is aimed to be used in kinaesthetic haptic devices. The brake design proposes a solution to the stiction problem which is common among the MR brake based haptic devices. This problem occurs when the brake is activated to constrain the motion of the handle in one direction and the user wants to move the handle in the other direction. The development process, which consists of 3D designing, Finite Element Analysis (FEA) simulation and mathematical modelling, aims to achieve the optimal design with high performance to volume ratio. The prototype design is constructed, and its performance is evaluated via experimental tests. A polynomial equation is calculated to fit the experimental current-torque data, which captures the hysteresis behaviour of the system. According to the test results, the applicable torque range of the prototype is from a minimum of 0.15 Nm to a maximum of 3.84 Nm and the bandwidth is calculated to be 63 rad/s.

Keywords: Magneto-Rheological brake, haptics, 3D design and modelling, FEA simulation, experimental characterization

## Introduction

The use of a motor-transmission system is a common solution in haptic device design since it can be used to apply forces/torques to the user and at the same time it can be used to provide a dynamic motion whenever necessary. Since the DC motor modelling is well studied and the capstan transmission systems are proven to provide smooth operation, most of the commercially available haptic devices are constructed by using this actuator-transmission system.

In kinaesthetic haptic devices, a greater portion of power spent is for displaying a rigid/stiff constraint. This fact causes problems in terms of stability and calls for cautious design procedure to meet the passivity equation below [1].

$$\mathrm{b} > \frac{\mathrm{K}}{2\mathrm{f}} + \mathrm{B} \qquad (1)$$

In the above equation b is the physical damping in the system K and B parameters are the maximum stiffness and damping that rendered in virtual environment and f is the sampling frequency. Therefore, to simulate higher stiffness with the haptic device either the physical damping or the sampling frequency should be increased. However, the increase in the physical damping would affect the minimum impedance of the device adversely.

One solution to the above problem is including a component that can provide variable physical damping to the system. It was introduced in [2] that the additional variable damping to the system can be provided by using a magneto-rheological (MR) fluid-based damper. In this case, (1) is revised to the following equation.

$$\mathrm{b} + \mathrm{b_c(H)} > \frac{\mathrm{K}}{2\mathrm{f}} + \mathrm{B} \qquad (2)$$

In the above equation $\mathrm{b_c(H)}$ is the additional damping provided by the MR-fluid based damper, which is a function of the magnetic field, H. Therefore, the major benefit of using a MR-fluid based brake is that it removes the adverse effect of the increase in the minimum impedance while providing much higher stiffness values with respect to commonly used motor-transmission systems.

Magneto-rheological fluid is a smart material which can exhibit different rheological characteristic if the fluid is exposed to the magnetic field. With the effects of magnetic field, the magnetic particles (usually iron particles) inside the carrier fluid align through the magnetic flux direction. The alignment of these particles changes viscosity of the fluid and the phase of the fluid to semi-solid form. Therefore, it is possible to vary the yield stress by changing the current on the coil that provides the magnetic field.

The controllable viscosity-based damping provided with MR-fluid is used for developing clutch, brake and damper systems. In terms of haptic device development, MR-fluids are usually used as brake systems that can provide a range of brake forces. In the previous works, the design of an MR-brake based haptic device is explained in detail [3] and a multi degree-of-freedom (DoF) haptic device was built by using an MR-fluid based design [4]. Some researcher even used the MR-brakes along with the conventional motor-capstan drive systems [5] to increase the z-width of the device by increasing the maximum stiffness of the system.

The common problem in the above-mentioned studies with MR-fluid based haptic devices is that once the MR-brake is activated to constrain the motion in one direction, although the user wants to move in the other direction, the motion in the other direction is also constrained. This is commonly called the stiction problem in MR-fluid based haptic devices. There have been studies to overcome this problem [6] however, this paper aims to provide a novel solution in the MR-brake design which cancels out the stiction problem without the need of any other active components or software precautions [7].

### A Brief Information on MR Brake

The most common configuration considering the disc type MR-brakes is the single-disc MR-brake. In order to simplify the understanding of the MR-brake design, this type of device is presented in this section. The performance of the device can be estimated with FEM simulation and analytical calculations. A single-disc MR-brake is shown in Fig. 1.

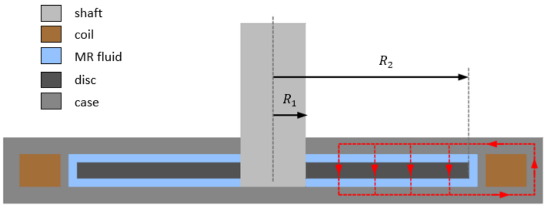


***Fig. 1****: Example of a single-disc MR-brake.*

The gap between the disc and the case is filled by MR fluid. The stranded wire is wrapped to the case in order to create a magnetic flux vertical to the MR fluid. When the electric current is run through the coil, magnetic field lines follow a path as shown with red dashed line. As the magnetic field is increased, the material structure of MR fluid changes from liquid to semi-solid form, which increases the yield stress of the MR fluid and generates a resistive force between disc and the static case.
MR fluid behaviour under the magnetic fields effect is modelled by using Bingham plastic formula in (3). In this model, shear stress $\tau$, is proportional to the yield stress $\tau_y$ of the MR fluid depending on the magnetic field strength H.

$$\tau = \tau_y(H) + \eta(\frac{dv}{dz}) \tag{3}$$

In the above equation, $\eta$ is the Newtonian viscosity and $dv/dz$ is the velocity gradient in the direction of the magnetic field. When Bingham plastic model is applied to the MR systems, the following formula is derived

$$\tau = \tau_y(\mathrm{H}) + \eta(\omega r/g) \tag{4}$$

where, $\omega$ is the angular velocity between input and static parts, r is the radius from the rotational axis, and g is the gap thickness which is filled with MR fluid. Considering the relation between the shear stress and the resistive torque, the output torque of an MR brake is calculated as $dT = r\tau\, dA$, where, T is the output torque and A is the active area of MR fluid inside the brake. Using the above-mentioned formulas, the following formula can be obtained for the resistive torque of a single disc MR brake.

$$T = 2\int_{R_1}^{R_2} 2\pi\left[\tau_y(H)r^2 + \eta\left(\frac{\omega r^3}{g}\right)\right]dr \tag{5}$$

As the angular velocity is getting closer to the zero as the MR fluid becomes semi-solid, the effects of the right side of the formula becomes relatively small than the effects of the field dependent yield stress. After making this assumption, the shear stress can be expressed with the field dependent yield stress. Then, the formula for the calculation of MR brake torque for single disc design becomes

$$\mathrm{T} \approx \frac{4\pi\tau_y(\mathrm{H})(\mathrm{R}_2^3 - \mathrm{R}_1^3)}{3} \tag{6}$$

where $R_1$ and $R_2$ are the inner and outer radius of the disc, respectively (see Fig. 1).

### Drum type MR brake design

There are two common types of MR brake design, which are named by the rotary part, as disc and drum. In the drum type MR brake, MR fluid is filled between the rotary drum and static parts. In this work, two inverse brakes are placed in a system to overcome the stiction problem. Even though the disc type MR brakes are easy to design and manufacture, the drum-type is chosen to develop more compact MR brake design.
Using formula (4) in the relation between shear stress and the resistive torque $dT = r\tau\, dA$, the output torque for the drum type MR brake is derived

$$T = 2\pi r^2 h\tau_y(H) + \eta\left(\frac{\omega r^3}{g}\right) \tag{7}$$

where h is the height of the drum in contact with MR fluid. As the viscous friction is neglected, the formula becomes

$$T \approx 2\pi r^2 h\tau_y(H) \tag{8}$$

in simplified form for the haptic applications. In order to increase the output torque in a compact volume, several drums are used in a brake. In the following, the formula (9) is modified to be used in multi-drum MR-brakes [8].

$$T \approx \sum_{i=0}^{n} R_i^2 \, 2\pi h \tau_y(H) \qquad (9)$$

$R_i$ represent the inner radius of the $i^{th}$ drum. MR fluid is in contact with $n$ number of drums. Based on a design $R_0$ value; $R_{i+1} = R_i + d + g$, where, $d$ is the thickness of the cylinders and $g$ is the MR-fluid gap thickness. The dimensions relating to the torque calculation are shown in the Fig. 2.

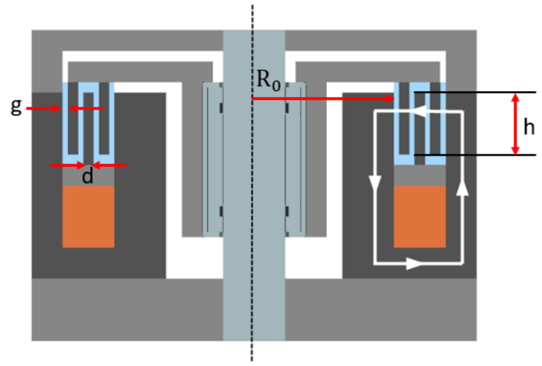


***Fig. 2****: Section view of the multi-drum type MR brake*

In (9), as previously stated, $\tau_y(H)$ represents the magnetic field dependent yield stress. $\tau_y(H)$ is found as 25.67 kPa by the magneto-static analysis from ANSYS according to design parameters, material selection and applied current.

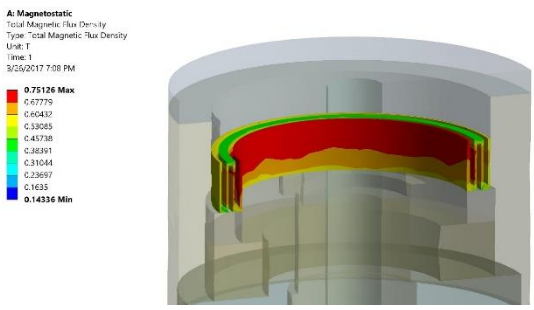


***Fig. 3****: FEA simulation result*

The parameters related to the radius and the height of the cylinders are defined after a series of simulations. In the final design, $R_0$ equals to 25 mm, $h$ is 9 mm, $d$ is 1 mm and $g$ is 0,5 mm. Using the given dimensions and the magnetic field dependent yield stress $\tau_y(H)$ found in the FEA simulation in (9), the output torque is calculated as 4.33 Nm.

### The Proposed MR-Brake Design

The new MR-brake design has two identical drum-type MR-brakes on top of each other. The cross-sectional view of the design is shown in Fig. 4. The two MR-brakes are mounted opposite to each other divided by a separator. The only rotating parts are the rotary cylinders that are fixed to the rotary part. The MR fluid is in between the rotary and the static cylinders. The rotary part is mounted to the shaft with a one-way clutch, which transmits the torques in one direction. In the case of a reverse direction motion, even though the magnetic field effect is on the MR fluid, the brake torque is not transmitted to the shaft since the rotary part is decoupled with the shaft. The second MR brake which is at the bottom side, uses the same design however, the one-way clutch transmits the torque in the opposite direction relative to the clutch in the above assembly.

Both MR brakes use separate coils to control directional brake function. For instance, considering the right-hand direction as the positive direction, the first one way-clutch couples with the shaft in the positive direction and the second one-way clutch couples in the negative direction. That means, when a braking torque is to be provided in the negative direction, the current to provide the necessary braking torque is applied on the second brake system. However, the shaft is still free to rotate in the positive direction.

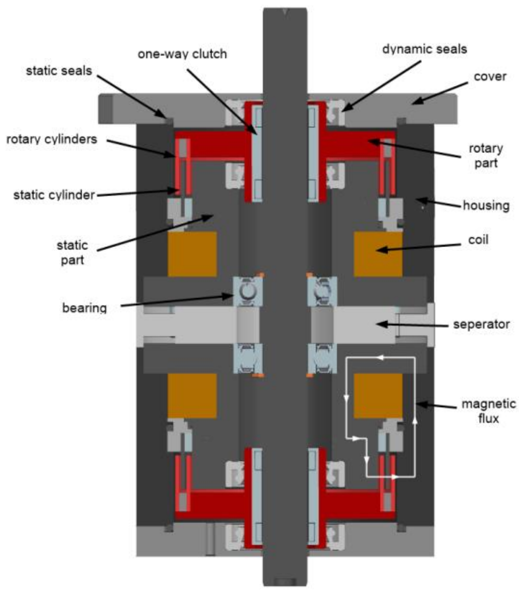


***Fig. 4:*** *The proposed MR-Brake design*

### Experimental Results

As the output torque is controlled by the applied electrical current, at first, it is important to experimentally obtain the relation between them. Current torque relation classifies the performance of the MR brake, i.e. maximum and minimum torque limits in the applicable current range. For the characterization, repeated sequence of sinusoidal current signal is applied, and the resistive torque generated by MR-brake is sensed. Hysteresis loop is observed in the current torque relation for both directional MR brakes. To control the MR brake between the upper and lower torque limits, fifth degree (quintic) polynomial function is fitted to experimentally obtained torque and the result is compared in Fig. 5.

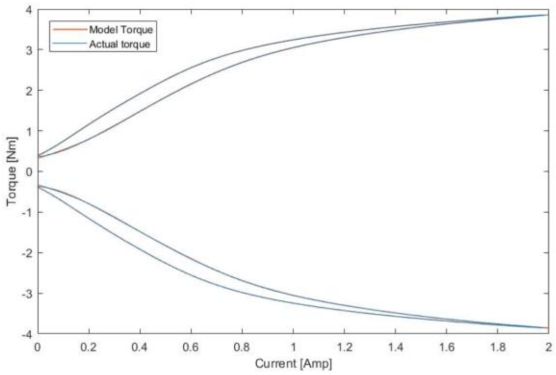


***Fig. 5.*** *Current-torque relation of both MR brakes.*

The minimum measured braking torques are 0.15 Nm and 0.4 Nm for first and second MR brakes at 0 A, and the maximum measured torque reaches 3.8 Nm for both brakes at 2 A. The experimental results are consistent with the predicted torque which is calculated in the design process.

The frequency response of the system is defined as the steady-state response of the system to a sinusoidal input signal. Transfer function of the both MR brakes are computed from the experimentally measured logarithmic gain and phase diagrams by System Identification Toolbox™ in MATLAB® software. In Fig. 6, experimental and estimated frequency response diagrams are compared for both MR brakes. The transfer function of the first MR brake

$$\frac{1}{1.791\times10^{-5}s^2+0.017s+1} \tag{10}$$

According to the results, both parts of the MR brake have second order transfer functions as presented in Table 2 and the bandwidths in the vicinity of 63 rad/s.

$$\frac{1}{2.309\times10^{-5}s^2+0.017s+1} \tag{11}$$

## Conclusion

A possible solution to the stiction problem in MR-brakes to be used in haptic devices is presented. Design steps of the bi-directional multi-drum type MR brake and verification tests of the prototype are discussed. The measured characteristics of the prototype are tabulated in Table 2.

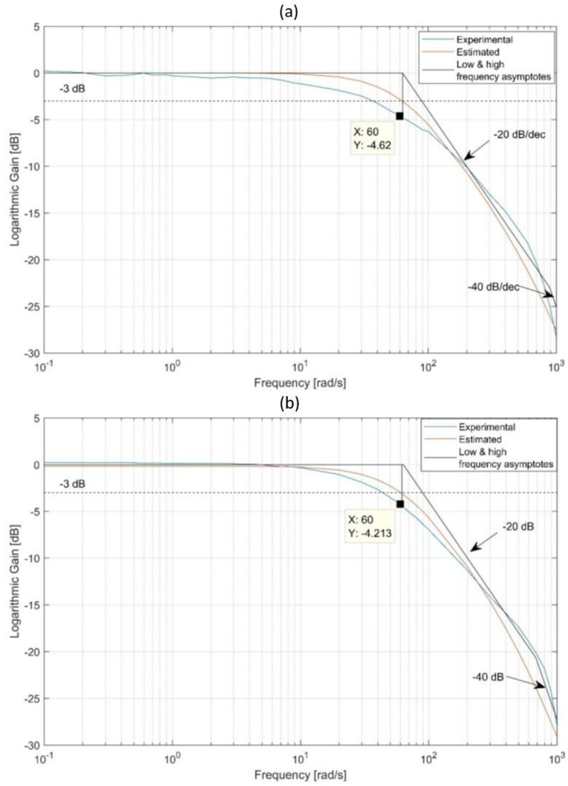


***Fig. 6****: Bode diagram of the (a) first and (b) second MR-brake.*

***Table 2:*** *MR brake specifications*

| **Category** | **Specification** |
|---|---|
| Product weight | 3.57 kg |
| Braking torque @ 2 A | 3.8 Nm |
| Off-state torque | 0.15 – 0.4 Nm |
| Bandwidth | 63 rad/s |
| External Diameter | 80 mm |
| Length | 124 mm |
| Coil wire dia. | 0.5 mm |
| Max. operational current | 2 A |
| Number of turns (coil) | 450 |
| Magneto-rheological material | MRF-122EG |
| Magnetic material | AISI 1008 Steel |
| Non-magnetic material | Stainless Steel and Aluminium |

Results indicate that both MR brakes have different static friction values, in other words, off-state torque as 0.15 Nm and 0.4 Nm. Although these static friction effects can be compensated for by using a motor coupled to the system, design modification especially for the sealing can provide better results. The difference stem from the manufacturing errors, i.e. axis eccentricity and out of tolerance parts. Even though there are enough holes for filling MR fluid and outlet for the air, uniform filling of the MR fluid was another difficulty.

The next stages of this study include design modifications to overcome the abovementioned design problems for a modified smaller version of this prototype. Using quintic function is sufficient to control MR brake between the torque limits, however, for the human experiments the controller shall include the hysteresis model [9]. Also, human experiments using a virtual reality simulation will be conducted which will provide a subjective comparison of the design with respect to the conventional actuation systems.

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## References

[1] J. E. Colgate and J. M. Brown, "Factors affecting the z-width of a haptic display," in *Robotics and Automation, 1994. Proceedings., 1994 IEEE International Conference on*, 1994, pp. 3205-3210: IEEE.

[2] J. An and D.-S. Kwon, "In haptics, the influence of the controllable physical damping on stability and performance," in *Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on*, 2004, vol. 2, pp. 1204-1209: IEEE.

[3] B. Liu, W. Li, P. B. Kosasih, and X. Zhang, "Development of an MR-brake-based haptic device," *Smart materials and structures,* vol. 15, no. 6, p. 1960, 2006.

[4] D. Senkal and H. Gurocak, "Spherical brake with MR fluid as multi degree of freedom actuator for haptics," *Journal of Intelligent Material Systems and Structures*, vol. 20, no. 18, pp. 2149-2160, 2009.

[5] E. Samur, L. Flaction, U. Spaelter, H. Bleuler, D. Hellier, and S. Ourselin, "A haptic interface with motor/brake system for colonoscopy simulation," in *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on*, 2008, pp. 477-478: IEEE.

[6] C. Rossa, J. Lozada, and A. Micaelli, "Design and control of a dual unidirectional brake hybrid actuation system for haptic devices," *IEEE transactions on haptics*, vol. 7, no. 4, pp. 442-453, 2014.

[7] M. Karabulut, B. Taner, and M. Dede, "MR Sıvısı ile Çalışan Haptik Kol Tasarımı-Design of MR-fluid based Haptic Paddle," *TOK 2015 Bildiri Kitabı,* pp. 867-872, 2015.

[8] M. G. Karabulut, "Development of MR-fluid based semi-active dampers to be used in haptic devices," İzmir Institute of Technology, 2017.

[9] A. Dominguez, R. Sedaghati, and I. Stiharu, "A new dynamic hysteresis model for magnetorheological dampers," *Smart materials and structures,* vol. 15, no. 5, p. 1179, 2006.