Design and Analysis of a Lightweight Disc-Type Magnetorheological Device

Okan Topcu, Yigit Tascioglu, and Erhan I. Konukseven

***Abstract* —The focus of this paper is the weight reduction of a disc-type magnetorheological (MR) device. Two different designs are proposed and investigated via finite-element analysis (FEA) to achieve the optimum combination of design parameters that result in the highest torque-to-mass ratio. The FEA is performed using the non-commercial FEMM package. Due to the symmetrical structure of the device, a 2D-axisymmetric model is utilized to simulate the magnetic flux density distribution. The resistant torque calculations are based on the Bingham plastic model, assuming low shear rate of the MR fluid. The results are compared with a baseline design from literature. It is shown that, with simple improvements, the torque-to-mass ratio of the proposed O-Type MR device is three times higher than the baseline design while producing a similar resistant torque.**

***Index Terms* — magnetorheological device, Bingham model, torque-to-mass ratio, FEMM**

I. INTRODUCTION

Magneto-Rheological (MR) devices make use of MR fluids, the apparent viscosity of which rapidly (e.g. <10 ms) increase under magnetic field and reverts back to normal when the field is removed [1]. Since the magnetic field can be generated by electromagnets integrated to the device itself, the behavior of the MR devices can be electronically controlled [2].

Most of the literature on the design and analysis of MR devices are concentrated on large scale dampers or brakes [3-4], where the primary aim is to increase the maximum resistive torque of the devices as much as possible.

Some recent articles on the application of MR devices in medical prosthetics and haptics [5-7] present miniaturized designs in which one of the main objectives is torque-to-volume ratio.

The main contribution of this work is to focus on the weight reduction of a disc-type MR device by considering dimensions, materials selection and electromagnetic circuit design. Firstly a disc-type MR brake from [8] is chosen as a baseline design and modeled for Finite Element Analysis (FEA) simulation. Then, the resistant torque of the baseline design is verified by Bingham model of the MR fluid. Next, two different lightweight designs, named the O-type and the U-type, are described and simulated to achieve the optimum combination of design parameters that result in the highest torque-to-mass ratio. Finally, the results are presented and the parameters of the final design are given.

II. DESIGN OF A DISC-TYPE MR DEVICE

A. *Torque Analysis of a Disc-Type MR Device*

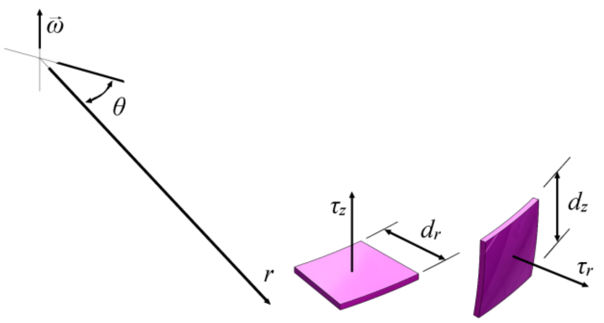

Fig. 1. Infinitesimal area elements of a disc-type MR device

The dominant resitant torque of disc-type MR devices originate from yield stresses at the surfaces of the disc (Fig. 1). These devices operate in direct-shear mode, in which the MR fluid is in between two surfaces that move with respect to each other. The produced resistant torque depends mostly on dynamic yield stress and viscosity of the MR fluid [2]. At low shear rates, behavior of the MR fluid is defined by simple but effective Bingham plastic model, given by;

$$\tau = \tau_y(H) + \eta \frac{\omega r}{h} \tag{1}$$

where τ is shear stress, which depends on dynamic yield stress $\tau_y(H)$, fluid viscosity η, angular velocity ω, fluid gap h, and radial distance r (see. Fig. 1).

The resistant torque of a disc-type MR device comes from two sources; shearing between the MR fluid and the axial surfaces of the disc, and shearing between the MR fluid and the thin radial surface of the disc. This can be modeled as;

$$dT = (2\tau_z dr + \tau_r dz) r^2 d\theta \tag{2}$$

Due to the thin structure of the disc, the second term in paranthesis can be considered negligible. Hence, the resistant torque is derived by integrating the shear stress only along the axial surfaces of the disc,

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$$T = 2\pi \int_{r_i}^{r_o} 2\tau_z r^2 dr \qquad (3)$$

where T is the resistant torque, r_i and r_o are the inner and outer radii, respectively. Substituting (1) into (3), the resistant torque is given by:

$$T = \frac{4\pi}{3}\tau_y(H)(r_o^3 - r_i^3) + \frac{\pi\eta\omega}{h}(r_o^4 - r_i^4) \qquad (4)$$

In (4), the first term is due to the MR effect and the second term is due to viscous flow. If the MR device is assumed to work at very small angular velocities, the influence of the second term becomes insignificant and can be neglected.

B. Baseline Design

A standard disk-type MR device, depicted in Fig. 2, is chosen as a baseline design. The parameters in Table I are taken from [8], which presents a study investigating the use of a similar MR device in a haptic device.

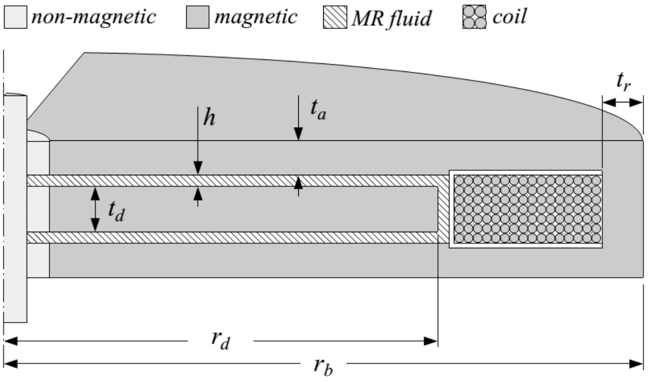

Fig. 2. Quarter-disc 3D model of the baseline design

TABLE I
PARAMETERS OF THE BASELINE DESIGN [8]

Symbol	Explanation	Value
r_b	brake radius	78 mm
r_d	disc radius	50 mm
t_d	disk thickness	5 mm
t_a	casing wall thickness (axial)	7 mm
t_r	casing wall thickness (radial)	10 mm
h	MR fluid gap thickness	1 mm
N	number of coil turns	95

The materials in Table II are applied to the 3D model of the baseline design and the total mass of the MR device is calculated as 2.786 kg.

For electromagnetic analysis, a non-commercial software package FEMM [9] is used. Due to the symmetrical structure of the device, a 2D-axisymmetric model is utilized to simulate the magnetic flux density distribution. The magnetic B–H curve of the MR fluid is obtained from the manufacturer datasheet [10].

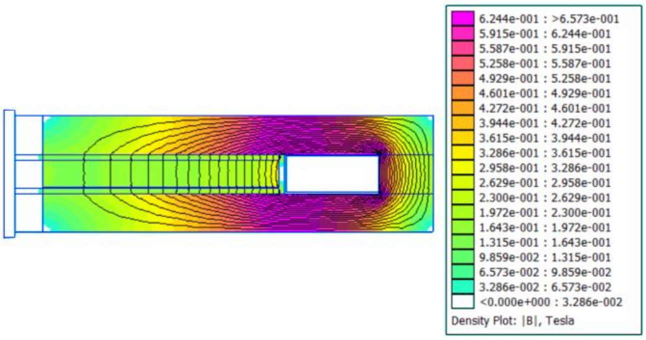

Fig. 3. FEA simulation of the baseline design

For comparison with the results in [8], this study considers only the MRF-132-DG, a medium yield stress MR fluid from the Lord Corporation. Also, for the same reason, the applied current in the simulations is set to 1 A. Fig. 3 shows the magnetic flux density of the baseline design. Including viscous effects at a constant angular velocity of 2π rad/s, the resistant torque is calculated as 4.478 Nm and the corresponding torque-to-mass ratio is 1.61 Nm/kg.

III. DESIGN ALTERNATIVES FOR WEIGHT REDUCTION

The weight reduction problem is to achieve the same or higher resistant torque with a lighter MR brake. Looking at the FEA results of the baseline design in Fig. 3, it can be seen that the flux density through the MR fluid increases from the center to the edge of the disc. The effect of this increase on the resistant torque is further amplified by the increasing moment arm.

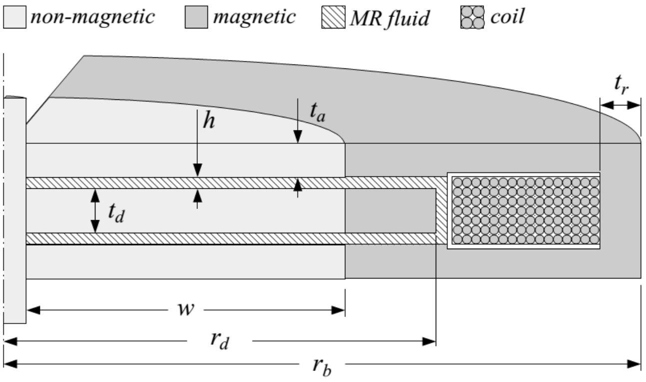

Fig. 4. Quarter-disc 3D model of the O-type device

The initial idea for a lightweight design is to replace the heavier magnetic steel at the central parts of the disc and the casing with the much lighter but non-magnetic acrylic resin, as shown in Fig. 4. For the remaining of this paper, this design will be called the “O-type” device. The dimension w denotes the radius of the non-magnetic material.

TABLE II
MATERIALS USED IN THE SIMULATIONS

Type	Material	Density
electromagnet coil	AWG-26 Copper Wire	8870 kg/m^3
magnetic material	1018 Low Carbon Steel	8000 kg/m^3
non-magnetic material	Acrylic Resin	990 kg/m^3
MR fluid	MRF-132-DG	2380 kg/m^3

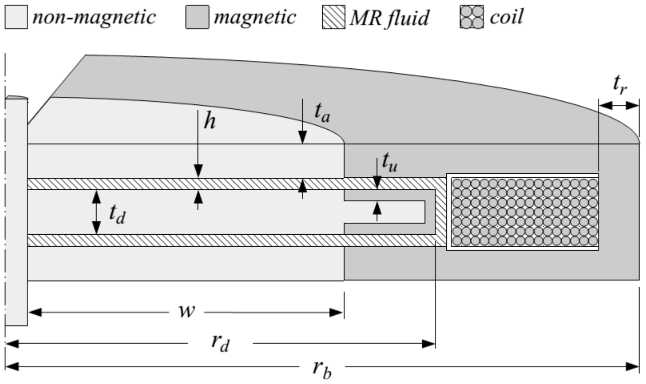

Fig. 5. Quarter-disc 3D model of the U-type device

Another design, named the “U-type”, reduces the weight of the O-type device further by using an acrylic disc with magnetic, steel covered surfaces only near the edge. The U-type design is depicted in Fig. 5 where t_u indicates the thickness of the steel cover.

IV. RESULTS AND DISCUSSION

To achieve the optimum combination of design parameters that result in the highest torque-to-mass ratio, the FEA simulations in the FEMM package are integrated with a MATLAB script, which calculates the mass and resistant torque of each simulated case.

For the first set of simulations, the volume of the MR device is kept constant. Also, in order to achieve better comparison with the baseline design, the parameters in Table I and the materials in Table II are applied to O-type and U-type devices. Coil current of 1 A is used in the simulations, and the viscous effects are calculated at a constant angular velocity of 2π rad/s. The variable parameters in the FEA simulations are listed in Table III.

TABLE III
VARIABLE PARAMETERS IN THE FEA SIMULATIONS

Simulation Set	Parameter	Range	Step	Applied to
1	w	5 – 45 mm	5 mm	O-type & U-type
	t_u	0.5 – 2 mm	0.5 mm	U-type
2	w	5 – 45 mm	5 mm	O-type
	t_d	1 – 7 mm	1 mm	O-type
	$t_a = t_r$	1 – 7 mm	1 mm	O-type

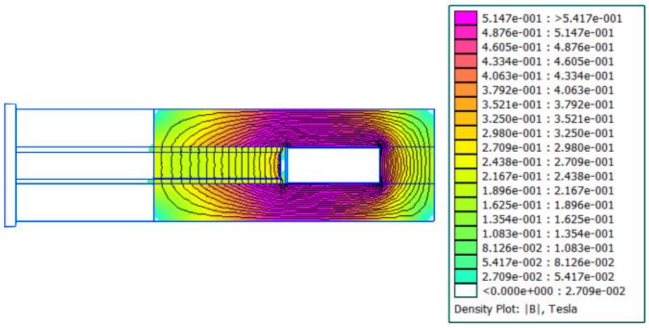

Fig. 6. FEA simulation of the constant volume O-type design with the highest torque-to-mass ratio

Fig. 6 shows the FEA result of the O-type MR device with the highest torque-to-mass ratio. At w = 25 mm, the O-type device achieved a resistant torque of 4.424 Nm with a calculated mass of 2.481 kg. The corresponding torque-to-mass ratio is 1.78 Nm/kg. Comparing with the baseline design, the O-type device results in 10.9% weight reduction while the torque loss is only 1.2%.

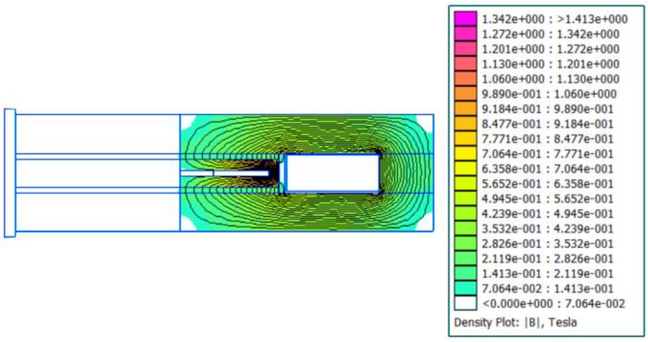

Fig. 7. FEA simulation of the constant volume U-type design with the highest torque-to-mass ratio

FEA simulation of the U-type MR device with the highest torque-to-mass ratio of 1.421 Nm/kg is shown in Fig. 7. Here, the optimal values of t_u and w are 2 mm, and 30 mm respectively. The calculated mass, 2.329 kg, is 16.4% less than the baseline design. However, the resistant torque of 3.309 Nm indicates an unexpected 26.1% torque loss due to the change in the magnetic flux path.

In the second set of simulations, only the O-type device is considered. This time, the objective is to achieve a design that produces a resistant torque within 5% of the baseline design with the highest torque-to-mass ratio. The volume of the device is also changed by simulating variable thicknesses for the disc and the casing walls (see Table III). Also, the cross-section of the coil is limited to 25 mm^2 which can easily fit 95 turns of AWG 26 wire (diameter = 0.405 mm).

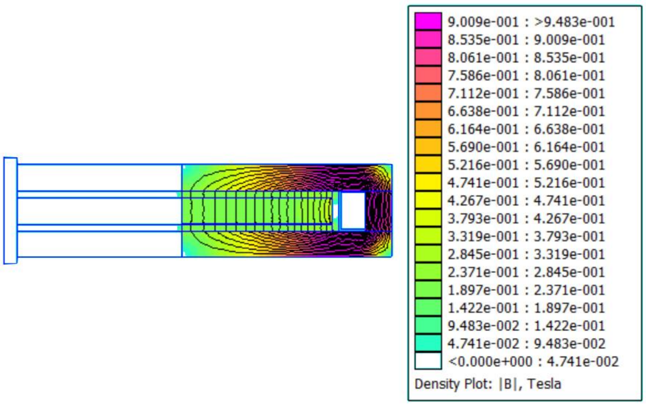

Fig. 8. FEA simulation of the final design

TABLE IV
PARAMETERS OF THE FINAL DESIGN

Symbol	Explanation	Value
r_b	brake radius	60 mm
r_d	disc radius	50 mm
t_d	disk thickness	4 mm
t_a	casing wall thickness (axial)	4 mm
t_r	casing wall thickness (radial)	4 mm
h	MR fluid gap thickness	1 mm
w	radius of the acrylic resin	25 mm
N	number of coil turns	95

Table IV lists the parameters of the final design and Fig. 8 shows the simulation result. The resistant torque and the mass are 4.345 Nm and 0.874 kg respectively. The corresponding torque-to-mass ratio is 4.97 Nm/kg. Furthermore, total volume of the MR brake is 61% less than the baseline design.

V. CONCLUSION

In this research work, a weight reduction method for a disc-type MR device is presented. Two different lightweight designs, named the O-type and the U-type, are analyzed via finite-element simulations. The work investigated materials selection and electromagnetic circuit design, by considering all of the significant geometric dimensions of a disc-type brake, in order to obtain the highest torque-to-mass ratio. All of the FEA simulations are carried out with the MRF-132-DG medium yield stress MR fluid from the Lord Corporation. Additionally, the same power input of 4.76 W is maintained for all of the designs by employing a constant outer radius of the disc and number of coil turns. The results showed that, with simple improvements, the torque-to-mass ratio of the proposed O-Type MR device is three times higher than the baseline design while producing a similar resistant torque.

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