RESEARCH ON REGENERATIVE BRAKE DESIGN USING MAGNETORHEOLOGICAL FLUID

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ABSTRACT

Regenerative braking is an advanced braking system that is used in conjunction with traditional braking systems, converting the kinetic energy of the braking process into electricity for reuse. With the research and design of regenerative brakes using magnetorheological fluid (MRF), the rotor shaft of the generator will be driven through the active shaft thanks to the power transmission properties of MRF during operation. When not in operation, the brake mechanism is not supplied with current, the oil layer is in a liquid state, the active shaft is not linked to the fixed shaft. When braking, the system will supply an electric current, and the MR fluid layer changes to a solid state to drive from the active shaft, linked to the fixed shaft, rotating the generator rotor. With the application of the regenerative braking using magnetorheological fluid, it is possible to optimize the power source on rear-wheel drive passenger cars. In this research, a new shape of regenerative brakes using magnetorheological fluid is designed. Using magnetic field simulation and analyzing calculated data to evaluate the efficiency of the field current and the generated voltage.

Keywords: *MR brake design, Regenerative braking, MRF.*

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1. INTRODUCTION

Research and presentation on the brake system using magnetorheological fluid on rear-wheel drive cars. The operation principle of the brake is based on the phenomenon of the change of viscosity and yield stress of magnetorheological fluid (MRF) exposed to a magnetic field [1, 2]. Magnetorheological fluid (MRF) is widely used in automobile systems such as clutches, shock absorbers, brakes, etc.

The application of MR oil on the clutch system [3] has made The transmittable torque can be 1.45 times greater than an existing disc-type clutch with the same input plate diameter.

In another document, [4] MR fluid is applied to the brake system again. The results showed that the mass of the optimized proposed MRB is significantly smaller than that of the con-ventional one at different values of the required braking torque.

Another study focuses on the "Geometric optimal design of a magneto-rheological brake considering different shapes for the brake envelope" [5] in this document is based on the designed MR fluid brake, different shapes of MRB envelope such as rectangular, polygon, and spline shapes, were considered from which the most suita-ble shape was identified. The results showed that the mass of conventional rectangular MRBs can be significantly reduced by using a 5-seg-polygon envelope.

This study applies magnetic field simulation to simulate and analyze calculated data to optimize the design of the brake system. It will help rear-wheel drive passenger cars save energy based on regenerative braking using magnetorheological fluid, it is possible to save energy through braking.

2. THEORETICAL BASIC

2.1. Basis for calculating renewable energy and binding force

T_{MRF}: Magnetic field braking torque in N.m

T_{visc}: Viscous torque in N.m

τ_h: Yield stress at a given magnetic field intensity in kPa

n: Number of surface of rotor perpendicular to magnetic flux lines and in contact with MR fluid

η: Plastic viscosity in Pa.s

z: Angular velocity of the disc in rad/s

R_i: Rotor outer radius in m

R_0: MR fluid shear gap in m

S: Conductor cross-section in mm^2

I: Current flowing through the square cross section in A

J: Allowable current density in A/mm^2

Table 1. Input parameters

η	g	R	n
0.11	0.01	0.08	2

Torque to rotate the generator:

$$M_{dm} = \frac{P_{dm}}{n_{dm}} \times 9.55 = \frac{P_{dm}}{\omega} \times \frac{1}{9.81} \quad (1)$$

To achieve the maximum pressing torque magnetic oil with high yield stress. The torque (T_{MRF}) generated by a magnetic oil layer can be calculated as follows [6]:

$$T_{MRF} = R_{MRF}^2 \int_{A_{MRF}} \tau dA_{MRF} \quad (2)$$

RMRF is the average radius of a magnetic oil layer. is the area of the active magnetic oil layer in the regenerative brake mechanism. The yield stress τ is calculated according to Bingham's model:

$$\tau = \tau_y \operatorname{sign}\left(\frac{du}{dy}\right) + \eta \frac{du}{dy} \quad (3)$$

τ_y is the yield stress and du/dy is the shear rate of the magnetic oil.

Yield stress (τ_y) can be approximated by experimental results:

$$\tau_y = k_0 + k_1 H_{MRF}^1 + k_2 H_{MRF}^2 + k_3 H_{MRF}^3 + k_4 H_{MRF}^4 + k_5 H_{MRF}^5 \quad (4)$$

H_{MRF} is the magnetic field strength. The value of the magnetic field strength (H_{MRF}) depends on θ and z of the cylindrical coordinate system of the rotor.

The pressing torque generated by the actuator will be calculated as follows:

$$T_{MRF} = R_{MRF}^2 \int_{A_{MRF}} \tau_y dA_{MRF} + \frac{2\pi\eta\omega z}{g} R_{MRF}^3 \quad (5)$$

Z is the length of the MR fluid layer, Aw is the cross-section

The ampere's circuital law states that the line integral of magnetic field intensity (H, expressed in ampere per meter A/m) about any closed path is exactly equal to the current enclosed by that path (I, expressed in ampere A) in a conductor as [7]:

$$\oint H.dL = I \quad (6)$$

Where C is the closed path of the line integral of H and NI is called the magneto-motive force (F, expressed in ampere-turns, Ats).

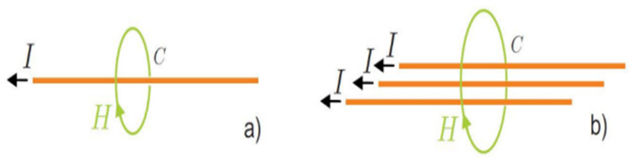

Fig. 1. Magnetic field intensity generated by a) single conductor; b) N conductors

The overall torque of the brake can be calculated using equation [8] bellow which is sum of field induced torque and viscous torque without magnetic field.

$$T = T_{MRF} + T_{visc} \quad (7)$$

where, TMR and Tvisc can be calculated using Eqs. (2) and (3) respectively.

$$T_{MR} = 2\pi\eta\tau_h (R_0^3 - R_i^3) \quad (8)$$

$$T_{visc} = \frac{\pi\eta\omega z}{2g} (R_0^4 - R_i^4) \quad (9)$$

And, τ_h can be calculated by using equation (4):

$$\tau_h = -0.8239 + 0.3668 \times H - 7 \times 10^{-4} \times H^2 \quad (10)$$

The calculate was carried out by the author's team with the Ford Ranger model:

Table 2. Parameters of Ford Ranger generator

P = 6 poles			
N quota: $Nq = 60 . \frac{f}{p} = 60 . \frac{60}{6} = 600$ (rpm)			f = 60Hz
Ford Ranger		R = 8cm = 0.08m	
P quota: Pq = 2625 W		Nq	Mq
U = 14V	I = 150A	600	41.78

2.2. Material properties of details

Material selection is an important part of the design and fabrication of regenerative brakes using MR magnetic fields. Materials used in design and manufacturing must meet the working conditions. SAE 1008 carbon steel as design material for the regenerative braking. Selection and use of MRF-132DG fluid as a solvent

3. DESIGN 3D MODEL AND SIMULATION

3.1. Basic parameters and design 3D model

Based on the data and parameters were carefully calculated, a regenerative brakes using magnetorheological fluid (MRF) is proposed to design:

Table 3. Parameters of the design

No.	Details	Parameters (mm)		
		Thickness	Height	Radius
1	Bark	25	210	160
2	Oil shield	15	130	
3	Coil	30	110	135
4	Bearings	40	50	90
5	Oil groove	10	110	

Use NX Siemens software to design a sample model of the part.

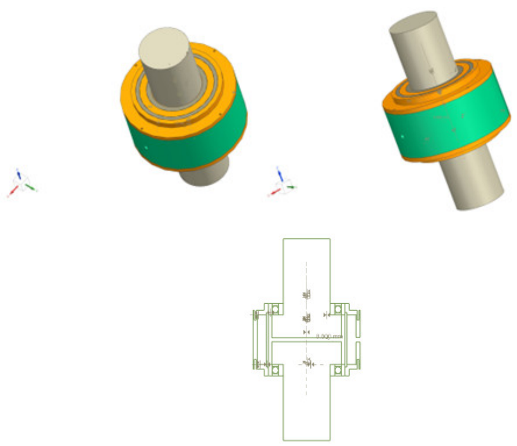

Fig. 2. Regenerative brakes using magnetorheological fluid (MRF)

3.2. Magnetic field simulation

When the car brakes, it will be excited to generate current, the study will investigate with current values from 100A to 250A with step is 25A.

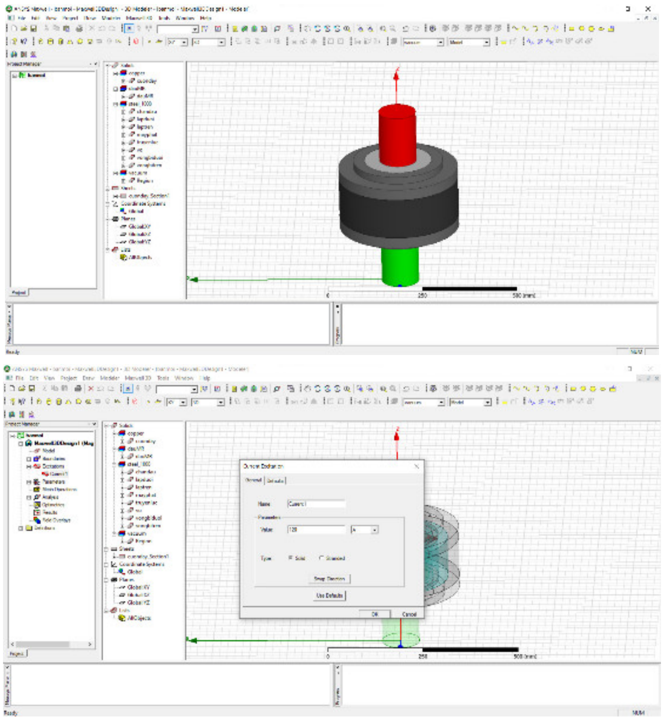

Fig. 3. Import model, setup parameter and current

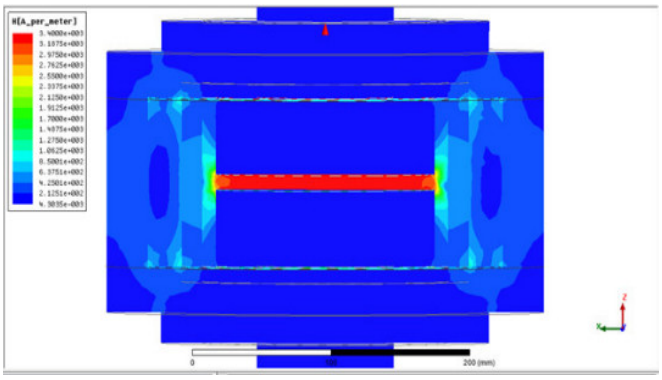

Fig. 4. Simulation results

3.3. Result and discuss

From the table bellow of rated voltage, we know that with each different winding cross-section, the voltage of the load current will be different.

Table 4. Load current Ampere (A) of copper wires

S \ J	3A/mm^2	4A/mm^2	5A/mm^2
0,9	1,91	2,54	3,18
1,0	2,36	3,14	3,93

To ensure the best working of the brake mechanism, the coil cross section is selected as a wire with a diameter of 1mm and an allowable load current (J) Ampere load per 1mm^2 of copper wire allowed in the range from 3A to 5A/mm^2. To brake with high standards and quality, we choose J 3A/mm^2.

Table 5. Load current Ampere (A) of coil

J \ NO	35	45	55	65	75	85	95
3A	82.6	106.2	129.8	153.4	177	200.6	224.2
4A	109.9	141.3	172.7	204.1	235.5	266.9	298.3
5A	137.5	176.8	216.1	255.4	294.7	334.1	373.3

No is number turns of wire, just wrap 85 turns of wire type with a cross-section of 1mm^2. From there, we can adjust the coil voltage in the range of 100 - 200A depending on the voltage supplied to line I ≤ 3A. But still ensure enough input current requirements and the number of turns is not too much, the load current is not too large.

The area of MR fluid connecting the two shaft surfaces has the greatest magnetic field intensity. The results for each current case are summarized in the following Table 6.

Table 6. The results of magnetic field intensity

10mm	Results		
Current	**Min**	**Max**	**H**
100A	861	918.83	890.1
125A	1376	1467.5	1421.7
150A	1911	2047.9	1979.7
175A	2659	2848.8	2753.9
200A	3188	3400	3293.8
225A	4273	4558.2	4415.8
250A	4620	5040.3	4830.3

Survey with different rotational speeds corresponding to the moments of car velocity: 800, 1200, 1600, 2000.

Table 7. Calculate Tvisc from ω

ω	$\omega_1 = 800$	$\omega_2 = 1200$	$\omega_3 = 1600$	$\omega_4 = 2000$
TVISC	1.152	1.729	2.305	2.881

Using the theoretical formulas, a table of torque and voltage data at the currents has been calculated.

Table 8. Calculate T_{MR}

Current	100A	125A	150A	175A	200A	225A	250A
τ_h	228.9	894.1	2018	4299	6387	12030	14561
T_{MR}	1.472	5.75	12.98	27.65	41.07	77.36	93.64

Table 9. Torque and voltage for each current and rotational speeds

I	T1	V1	T2	V2	T3	V3	V4	T4
100	2.6	0.9	3.2	1.1	3.8	1.3	4.4	1.5
125	6.9	2.3	7.5	2.5	8.1	2.7	8.6	2.9
150	14.1	4.7	14.7	4.9	15.3	5.1	15.9	5.3
175	28.8	9.7	29.4	9.8	30.0	10.0	30.5	10.2
200	42.2	14.1	42.8	14.3	43.4	14.5	44.0	14.7
225	78.5	26.3	79.1	26.5	79.7	26.7	80.2	26.9
250	94.8	31.8	95.4	32.0	95.9	32.1	96.5	32.3

By using these data sheet, some charts are built.

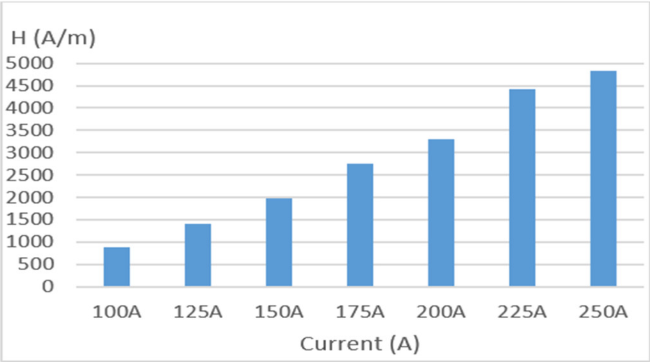

Fig. 5. Magnetic field intensity graph

From the graph can see that when the field current value increases, the magnetic field value also increases. The magnetic field value will be proportional to the field current value.

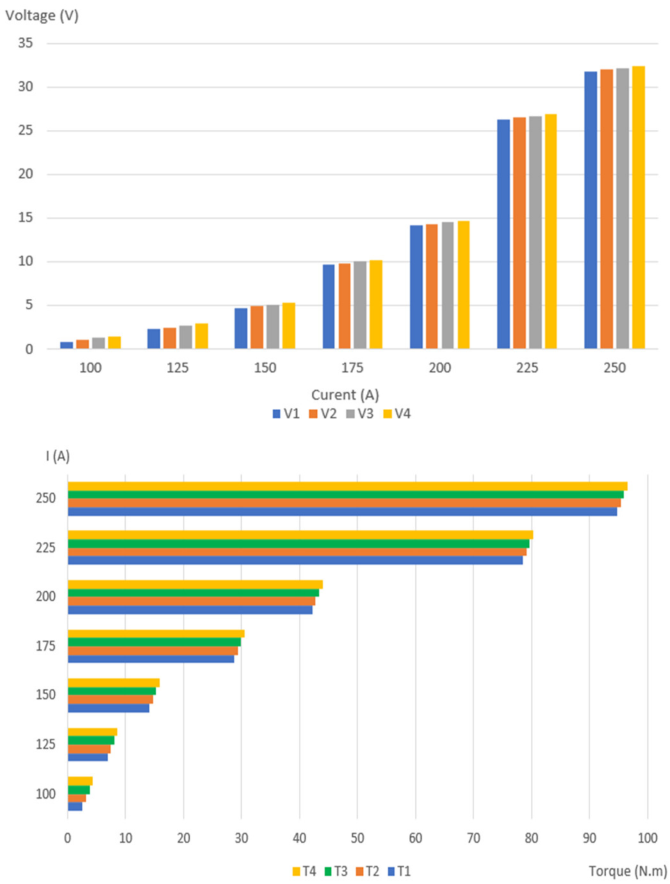

Fig. 6. Voltage graph and Torque graph

And with varying voltage values, we get different regenerative voltage values. This regenerative voltage value will depend on the generated torque value compared to the rated torque value of the generator with the smaller the generated torque, the smaller the regenerative voltage. The regenerative voltage value is proportional to the generated torque value of the MR. Actuator where the value of the torque force produced is proportional to the value of the field current.

From the torque graph, with different angular speed input parameters, different torque will be generated. The torque values are proportional to the field current values. With field current of 200A, the obtained generator voltage is stable and approximates the rated value of the generator.

4. CONCLUSIONS

With the value of 200A, the generated torque is approximately equal to the rated torque of the generator, the generator will operate at the rated value and generate the rated regenerative voltage value. Through the above values can be determined with the current value of 200A, the generator will operate and regenerate the best voltage, so that we can determine the stable operation level corresponding to the best field current value is 200A. With smaller currents, the efficiency will not reach 100%.

Need a solution to generate the most stable, and efficient currents, can take excitation current from ABS or can design a separate device. This will be the next research direction of the author's team.

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