JST: Engineering and Technology for Sustainable Development
Volume 33, Issue 1, March 2023, 042-049

Design and Simulation of Magnetorheological Brake Supporting Downhill Van Truck

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Abstract

Depressing the brake when the vehicle is moving downhill for a long time will have a bad effect on the car's brake system. Typically, the phenomenon of friction, wear, and temperature rise occurs at the brake pads. These can be the causes of brake failure. This paper presents the idea of designing and simulating magneto-rheological brake (MRB) model to assist van trucks downhill without interfering with the traditional braking system. Research on brake models using: Magneto-rheological fluid (MRF), a smart material that is gradually being applied in many fields of science and technology. The operation of this type of brake is based on the inherent advantages of MR fluids such as continuously changing dynamic range and fast response, actively changing the viscosity of the fluid when changing the magnetic field applied to the coil. In order to improve safety and initiative in the braking process of the car. The study presents the process of calculating and simulating the braking torque generated from this brake model. Thereby helping to open a new direction for the traditional brake system in cars as well as contributing to the development of the automobile industry in general.

Keywords: Magneto-rheological fluid, magneto-rheological brake, braking torque.

1. Introduction

Small van trucks are popular vehicles in the Vietnamese market that moving in Vietnam's traffic terrain often have to go downhill. When a small van truck that has weight goes downhill with the slope at an angle, it is subjected to a force, thereby generating an acceleration, increasing the vehicle's speed, and causing danger to the movement. Usually, the driver will use the traditional brake to brake and reduce speed. The problem is that if a van goes downhill for a long time, the long braking time will generate a lot of heat, causing wear of the brake pads and damage to the brake quickly. Then there will be costs for repairing or replacing new brakes for the vehicle. Considering the car is going downhill, we need to calculate the downhill torque caused by the acceleration.

In the car's layout, the power brake is installed behind the cardan shaft, and in front is the bridge cover due to the pedestal. When installing more brakes, we need to reduce the length of the cardan and install other accessories and brackets for the magnetic brake. This structure helps the car maintain the desired speed going downhill, much like riding on a flat road without affecting the original vehicle. This study will present the design and assembly of the brake mechanism, a preliminary calculation of the torque generated from the magnetic brake, and the stability check of the platform.

When arranging the magnetic brake on the vehicle, it is necessary to ensure that it does not affect the original structure of the vehicle. Some brake layout options are given:

- Option 1: Install MRB in parallel with traditional brake systems;
- Option 2: Install MRB instead of traditional brake;
- Option 3: Install the MRB on the powertrain.

With option 1, the arrangement of the magnetic brake parallel to the traditional brake is not feasible because there is no installation space. In option 2, the magnetic brake has not yet produced a large enough torque to replace the traditional brake, so option 2 is also not suitable. Instead, option 3 is perfectly suitable for mounting on the vehicle's powertrain, focusing on the task of supporting the vehicle downhill.

With the arrangement of the magnetic brake on the powertrain, the problem is related to the cardan shaft. Due to the change in angle, the length also changes, leading to translational motion into the gearbox output, so the arrangement of the magnetic brake will be more complex because the kinematics of cardan shaft rotation must be ensured. While the arrangement of the magnetic brake at the back of the

ISSN 2734-9381
https://doi.org/10.51316/jst.164.etsd.2023.33.1.6
Received: April 15, 2022; accepted: November 30, 2022

cardan shaft in front of the active bridge cover overcomes this problem, according to option 3, the magnetic brake will be installed between the cardan shaft and the active bridge cover. To make room for the MR brake, the cardan shaft is shortened by an amount of 0.1 m in length.

The Magneto-Rheological (MR) oil disc brake is a device that transmits torque by means of the shear force of the MR fluid. The liquid is introduced between the rotating and stationary discs, and a magnetic field is applied to the liquid. In the study of the group of Egyptian authors E.M. Attia, N.M. Elsodany, H.A. El-Gamal, M.A. Elgohary [1], a complete test rig for MR fluid disc brakes, is introduced. Experiments were performed to measure the braking torque and shaft speed during braking, and the results were performed at different voltage inputs to the brake.

In addition, theoretical analysis for both MR brake and the mechanical system was developed and numerically solved using finite difference method and MATLAB software. The influence of input current on MR brake, fluid viscosity, and design parameters are considered. The experimental results were performed to show that both angular velocity and braking torque are obtained as responses during braking. The comparison between the braking torque obtained from theoretical and experimental work shows consensus when the voltage is 2 V at 150 rpm and favorable when the voltage is 2 V and 3 V at 250 rpm.

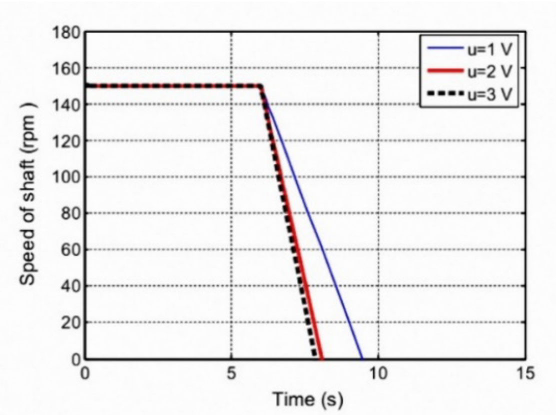


Fig 1. Comparing shaft deceleration time with different currents.

The research team's goal was to design and simulate a high-performance MR brake with high transmission torque, long-term stability, and simple construction. The ability to generate a torque of MR brake depends heavily on the characteristics of MRF, in particular, the rheological properties of both MRF when changing the magnetic field. The transmission torque equation for disc brakes is derived based on the Bingham fluid models. Also, in the study of author N.Q. Hung and his team presented a new configuration of the dynamic magnetic fluid-based brake with multiple coils placed on each side of the brake housing (magnetic fluid-based brakes). Side-coil motor is proposed, optimally designed, and evaluated [2]. This configuration providesd higher braking torque and is more compact in size than traditional magnetic fluid based brakes.

The proposed dynamic magnetic fluid-based brake torque is then analyzed based on the Bingham plastic rheological model of the dynamic magnetic fluid. Optimization of the proposed multi-coil magnetic fluid-based brake, magnetic fluid-based brake with one coil located on each side of the brake housing (single coil magnetic fluid-based brake), and the conventional magnetic fluid–based braking is then performed considering the maximum braking torque and the mass of the brake. Based on the optimal results, enhanced performance characteristics of the proposed magnetic fluid-based brake are found. In addition, test works are conducted to confirm the performance of the proposed multi-branch magnetic fluid-based brake.

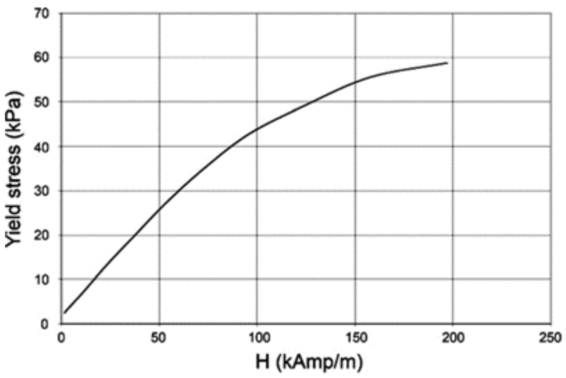
It can be seen that many research groups have focused on exploiting the potential applications of MR magnetic oil, wishing to create MR brake devices on the test platform with compact structure, high braking efficiency, high simulation value. However, very few studies have delved into the application to a specific moving object.

Therefore, in this paper, the authors focus on studying the application of an MR brake design with a toothed disc structure installed on a small truck to support the vehicle when going downhill. This device works completely independent of the main brake system to actively generate braking torque when there is a change in the slope of the road, ensure a stable speed of the vehicle and increase the service life for traditional brake systems. By using simulation model the simulation results, the MRB's performance at various operation conditions was investigated.

2. Methodology

2.1. Magnetic Oil Theory

Magnetorheological fluid is a smart material discovered in the 1940s, belonging to the family of rheological materials with the ability to change phase under the action of a magnetic field. Soft ferromagnetic or paramagnetic particles (0.03 ~ 10 μm) dispersed in the carrier liquid. As long as the magnetizable particles exhibit low levels of coercivity, a variety of ceramic metals and alloys can be used in the composition of MR fluids. Typically, the MR particles are pure iron, carbonyl iron, or cobalt powder, and the carrier is a non-magnetic, organic, or liquid, usually silicone or mineral oil [3]. MR oils can be used to build integrated, silent, rapidly changing mechanical systems, enhanced through magnetic field variation. Some ferromagnetic materials can be used as magnetic particles dispersed in a carrier fluid (mainly oil or water) to produce a magnetic effect. In the absence of a magnetic field, the MR particles are randomly distributed in the liquid. When the MR liquid is subjected to any magnetic field, the particles will acquire a dipole torque consistent with the field flux lines under the influence of a magnetic field, the dispersion of the MR particle changes. Then, the MR particles acquire a dipole torque consistent with the external environment and form chains with a clear direction. This chain formation causes reversible yield stress in the fluid. In addition, the dynamic stress of the MR fluid can be adjusted continuously and rapidly because it responds to the strength of the applied magnetic field. When this phenomenon is analyzed at the microscopic scale, it can be seen that it leads to the formation of linear beads, which results, at a large scale, in a solid-like MR ensemble. As a result, liquid-based MR devices have inherent advantages such as dynamic continuously variable range and fast response.



(a)

Fig. 3. Describe the effect of magnetic field on stress.

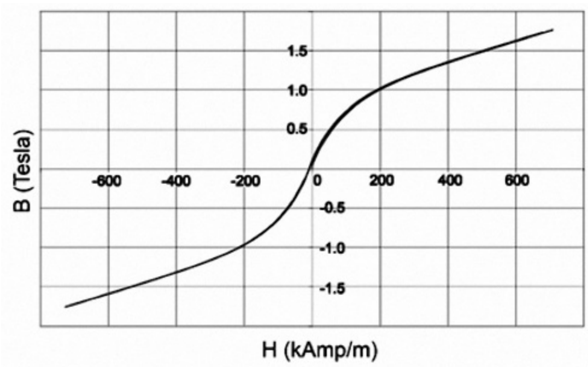


Fig. 4. Magnetic particle Saturation.

The important parameter for MR fluids is the dynamic shear stress (τ_y), which is the maximum stress the fluid can withstand before it begins to flow. This value τ_y is affected by magnetic fields, as shown in Fig. 4 showing manufacturer-supplied technical data sheet for commercial MR 140-CG fluid from LORD Corporation [4]. Obviously, as H increases, the fill increases, but there is a limit due to the saturation of the magnetic particles.

From Fig. 4, we see that, no matter how high the flux, through the smart application of coils or permanent magnets, the maximum power dissipation reaches a stable level due to the limit of τ_y . Therefore, one possible way to enhance the yield stress of MR fluids is to select granular materials with greater magnetic saturation [5].

2.2. Magnetic Field Theory in Altair Flux

Altair Engineering Inc. is an American multinational information technology company, that provides software and cloud solutions for simulation, IoT, high-performance computing, data analytics, and artificial intelligence. Altair Flux is a software module from Altair Engineering that specializes in supporting electromagnetic field simulations. The current I and the magnetized material create a magnetic field H [6].

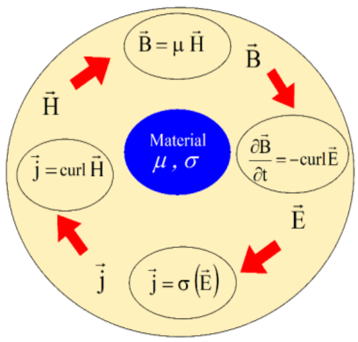


Fig. 5. Aggregate relationships in Flux

Now let's get into the specific formulas that describe the Fig. 5. diagram.

The current (*j=current* density) produces a magnetic field:

$$\text{Curl } \vec{H} = \vec{j} \tag{1}$$

The flux of B is conservative:

$$\text{Curl } E = -\partial B \partial t \text{ div } \vec{B} = 0 \tag{2}$$

dB/dt and E are linked:

$$\tau = \tau_y + \eta\dot{\gamma} \tag{3}$$

From Ohm's law we have:

$$\rho\vec{j} = \vec{E} \tag{4}$$

General formula for magnetic induction is:

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \tag{5}$$

Table 1. Explaining the symbols.

Symbols	Designations	Usual units	Equivalent units
ϕ	Flux	Wb	Vs
$\vec{B}$	Magnetic induction	T	Vs/m^2
$\vec{H}$	Magnetic field	A/m	A/m
$\vec{J}$	Magnetic polarization	T	Vs/m^2
$\vec{M}$	Magnetization	A/m	A/m
$\mu = \mu_0\mu_r$	Permeability	H/m	Vs/m
μ_0	Vacuum permeability $4\pi 10^{-7}$	H/m	Vs/m
μ_r	Relative permeability	-	-
$\vec{j}$	Electric current density	A/m^2	A/m^2
$\rho = \frac{1}{\sigma}$	Electrical resistivity	Ωm	V.m/A
L	Inductance	H	Vs/A

In vacuum, the value of magnetic induction is

$$\vec{B} = \mu_0 \vec{H} \quad (6)$$

Table 1 explains the symbols and coefficients used in the above formulas in theory, with the corresponding units used when working with Altair Flux:

In Altair Flux, for most of the models, the $B(H)$ dependence is a univocal relationship: one value of B corresponds to one value of H and vice versa.

Altair Flux defines two types of materials: Hard and Soft. For each type of material, through building mathematical models and approximations, we have $B(H)$ curves and the corresponding behavior of each material when an electric current is applied.

The characteristics to note for hard materials are:

- Special $B(H)$ curve for residual induced B_r and forced field H_c,
- $J(H)$ curve to evaluate demagnetization,
- Curie temperature for thermal stability assessment.

Characteristics to note for soft materials in static mode include:

- Saturated Magnetic Polarization J_s, Maximum relative permeability μ_r max,
- Remaining induced B_r and H_c coercive field on semi-static period,
- Curie temperature.

2.3. Magnetic Brake Structure

As analyzing the advantages and disadvantages of the above installation options, in order to match the installation space under the vehicle and the rotation of the components in the powertrain, the selected structure is in the form of plates round disc put together.

The magnetic brake is coupled between the cardan shaft and the active bridge housing at the mounting position with flanges (Fig. 6). In the assembled structure of this vehicle, there is an additional bolt holder with an active bridge cover and magnetic brake, the purpose is to keep the magnetic brake stable when the vehicle is operating and when braking. The main structure of the MRB kit includes following.

- Rotor is caught with cardan shaft, active bridge shell, trapezoidal disc profile, trapezoidal angles of magnitude 30 degrees [7].
- The brake outer shell is assembled by steel plates, which have round holes drilled to catch bolts and holes to install coils.

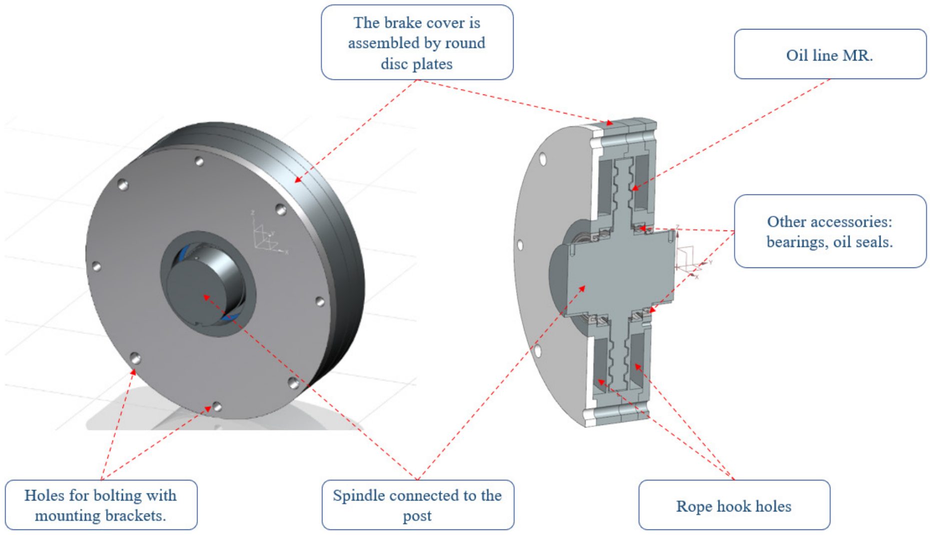


Fig. 6. Magnetic brake construction.

Magnetic oil is introduced into the area between the rotor and housing, the outside of the housing has an oil pump hole and is covered by the oil pump breast. The brake housing and the rotating disc are held together through ball bearings and oil seals. Bearings and oil seals are both selected as standard, capable of withstanding a large number of revolutions and torques in operation, and comfortable in working conditions.

2.4. Theoretical Basis for Calculating Brake Torque

Fig. 7 presents the structure of the MRF brake. Calculation basis based on Bingham fluid model equation:

$$\tau = \tau_y + \eta\dot{\gamma} \tag{7}$$

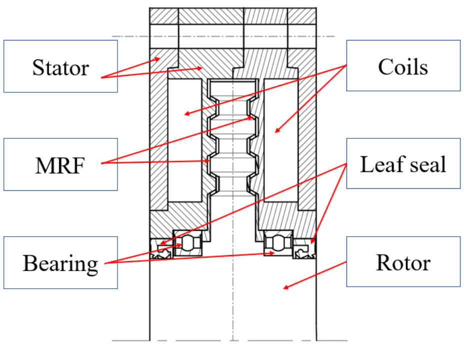


Fig. 7. Description of brake structure with MRF

The torque generated from area E has a linear method to the direction of the rotor rotation, areas A has a linear method to the direction of the rotor rotation at an angle of 30 degrees, and area has a linear method perpendicular to the direction of rotation rotor. The analyze specific computational areas at the MRF layer are presented in Fig. 8.

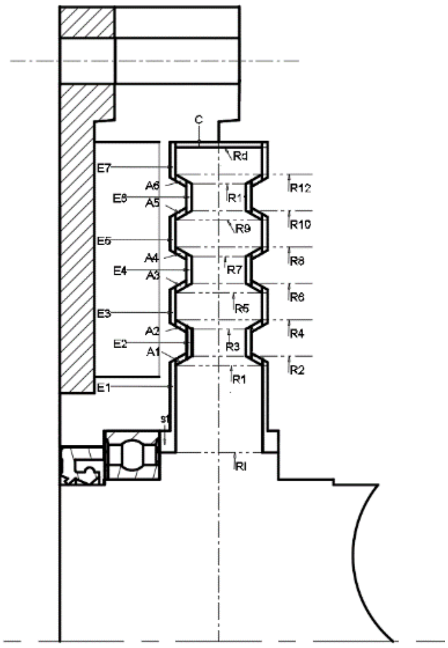


Fig. 8. Analyze specific computational areas at the MRF layer.

2.5. Oil Material MRF 140-CG

LORD Corporation has been working with controllable fluids since the 1980s and is presently the largest global supplier of commercial MR Fluids. Lord currently offers several oils:

- MRF-140CG
- MRF-132DG
- MRF-122EG
- MRF-126LF
- MRF-140BC

Table 2. MRF properties [4].

Typical Properties	
Appearance	Dark Gray Liquid
Viscosity, Pa-s @ 40°C (104°F)	0.280 ± 0.070
Density (g/cm³)	3.54-3.74
Solids Content by Weight, %	85.44
Operating Temperature, °C	-40 to +130

Each type of oil has different type of characteristics, working parameters, and states of operation. In this study, the team used the oil code MRF-140 CG to simulate the results. According to the documentation from LORD, we have the following material parameter value table and its properties (Table 2).

Besides, in order to facilitate the conversion from the magnetic field *H* to the corresponding stress τy, by applying the method of least squares curve fitting to the fluid properties, the approximate polynomial of yield stress according to the determined magnetic field [8]:

$$\tau_y = f(H_{MR}) = k_0 + k_1 H_{MR}^1 + k_2 H_{MR}^2 + k_3 H_{MR}^3 + k_4 H_{MR}^4 + k_5 H_{MR}^5 \quad (8)$$

where H_{MR} is the magnetic field strength generated from the MRF - 140CG, with the following coefficients: k_0 = 1.9; k_1 = 0.61; k_2 = -0.002; $k_3 = 2.69 * 10^{-6}$; $k_4 = -7.52*10^{-9}$; $k_5 = 1.76 * 10^{-11}$. With the related formulas in Flux presented, the generated magnetic field strength *H* will be applied to the above formula to calculate the shear stress for MR oil, from which the research team can calculate the torqueum generated by MRF.

2.6. Building Simulation Models

In this study, MRB was built by CAD model with SIEMENS NX CAD software, then built by finite element model with HYPERMESH tool and tested the stability using Flux solver of ALTAIR ENGINEERING.

Simulation material is C45 steel.

Boundary condition are two copper coils in the MRB cavity, the current flowing through the copper wire is cotrolled with a given value.

The finite element model is built with a mesh size 4 mm, 337050 nodes and 1496943 elements (Fig. 9).

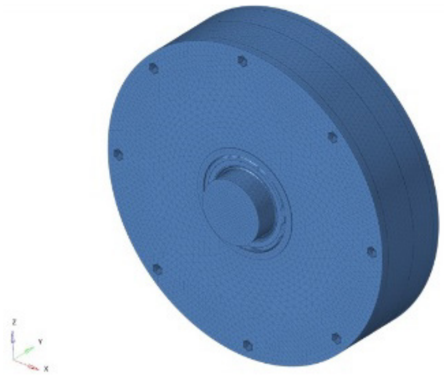


Fig. 9. Finite Element Model of MRB.

Table 3. C45 steel material specifications [9]

Material	Young module (Pa)	Poisson	Yield stress (MPa)
Steel C45	2100000	0.3	310

The materials used in the problem are C45 steel and MRF-140CG oil with parameters according to Table 3.

Simulated boundary conditions: Put in 2 coils of brake unit, apply a DC current to 2 coils.

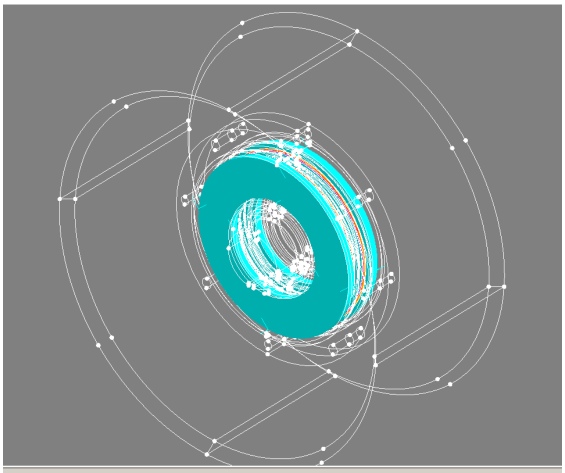


Fig. 10. Hollow (non-mesh) coil model.

Table 4 shows the coil current, number of turns and wire diameter used in the simulation.

Table 4. Simulation cases

	Case 1	Case 2	Case 3
Coil diameter (mm)	0.5	0.6	0.7
Number of turns	1600	1100	800
Current (A)	3.5	5.5	7.5

Conclusion: The study presented the structure of disc MR brake and gave a method to calculate the torque generated when the MR brake works in some conditions when changing coil diameter, number of turns, current value power applied by simulation method.

3. Result and Discussion

Using the Altair Flux solver, the calculated torque output at each area is shown in the Table 5. After applying the above formula, the study obtained the results of the overall torque generated by the MRB at the operating conditions.

Note that: The total torque generated by the MRB with the structure and some working conditions gives a value of about 145 Nm, in which the local torque generated in the Tc region gives the largest value. In general, this value satisfies the initial conditions of the problem when overcoming the torque generated when the vehicle goes downhill.

For the purpose of creating a brake model installed on the van truck, overcoming the problem posed at the beginning of the problem, The research team has chosen the option of 0.6 mm wire, number of turns: 1100, current: 5.5 A . With these parameters, the magnetic braking torque generated by the MRB is 144.73 Nm, which can overcome the torque generated when the vehicle is going downhill. This result shows that the simulation MRB torque is similar to the experimental result.

In addition, when performing calculations using the theory of magnetic fields according to Ampere's law, chose the value l as the average size of the winding. Next, from the formulas according to Ampere's law, we can calculate the magnetic field H.

The study calculate the length value is the circumference of the coil. Thus, the research team compared two methods of calculating magnetic field H as follow:

Method 1: We calculate H through classical formulas in Altair Flux, then look up experimental graphs to get yield stress.

Method 2: Using Altair Flux to simulate the finite element MRB, the research team obtained the magnetic field strength H, then through the formula (8) to calculate the yield stress. This work has been done in the above steps.

The formula for calculating torque is applicable to both methods. After having the results of yield stress calculation according to each method, the research team calculated the moment according to each specific area of the oil layer at areas A, E, C, Sf. Then calculate the total torque generated by the MRB and compare the methods. The results are shown in Table 5.

Table 5. Table comparing experimental graph and empirical formula

Method	Case 1	Case 2	Case 3
Method 1	60.51	69.67	69.40
Method 2	135.30	144.73	143.74
Scale factor	0.45	0.48	0.48

Note that: Compared with the calculated value according to the formula, the calculation of yield stress through the Lord graph gives a smaller torque (about 0.5 times).

We can see that: The problem of overcoming the vehicle's acceleration is solved, the additional structure still ensures the originality of the vehicle when operating, the brake mounted on the powerstrain is supported, durable enough for working conditions. From the CAD model, the research team will conduct processing and installation plans for the purpose of practical testing, thereby evaluating the working ability of the MRB concept and the applicability of the MRF.

The main disadvantage of this structure is that the generated braking torque is still low, the safety factor is approximately 1, which has not met the expectations of the research team.

4. Conclusion

In this research, a MRB simulation model was completely established. Based on this simulation model, the braking torque was investigated in various operating conditions. The maximum simulation brake torque was almost the same as the experimental result. These values were 144.73 and 145 Nm, respectively. From the comparison between experimental results and simulation results, all of the results with test cases are the same, so the MRB simulation model has good accuracy in prediction of MRB performance in further studies.

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