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Working Principle of Elevator Traction Transmission Device Based on MRF

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Abstract: This study aims to develop a novel Magneto-rheological Fluid (MRF) elevator traction transmission with a high-torque capacity. The MRF device has the property that transmitting torque and braking torque values changes quickly in response to an external magnetic field strength. In this study, the fundamental design method of the cylindrical MR traction transmission device is investigated theoretically. A Bingham model is used to characterize the constitutive behavior of the MRF subject to an external magnetic field strength. The theoretical method is developed to analyze the torque transmitted by the MR fluid within the design. An engineering expression for the torque is derived to provide the theoretical foundation in the design of the coupler and brake. Based on this equation, the volume and thickness of the annular MRF within the coupler and brake is yielded after algebraic manipulation. The study shows the design of the MRF traction transmission conforms to the torque requirements for elevator's safety. It certifies that the appropriateness of the experimental design and method, the analysis and interpretation of the data are sufficiently.

Key words: MRF, working principle, traction transmission device, torque

INTRODUCTION

A Magneto-rheological Fluid (MRF) is a type of smart fluid that has emerged in recent years. MRF can change itself from a liquid state to a solid state reversibly and rapidly under magnetic field and the shear yield stress can be controlled and adjusted according to the change of the magnetic field. The effective control of elevator transits through using the MRF elevator traction transmission designed by the MR technology to through changing MRF shear stress which the output torque and output speed could be controlled by electromagnetic. The research direction for elevator driving technology is to develop the brake and continuously variable traction transmission system based on MR technology which should satisfy the requirements such as energy conservation, environmental protection, working conditions, safety, comfort and so on. So, the study on MRF technology and the development of relevant equipments has extensive and profound significance in the field of traction transmission engineering. It certify that we have participated sufficiently in the work to take public responsibility for the appropriateness of the experimental design and method and the collection, analysis and interpretation of the data.

The elevator is a kind of transportation tool that is indispensable to high-rise buildings. The structure of the elevator is shown as Fig. 1. With the building scale becoming larger and larger, more and more social attention has been paid to the elevator in such aspects as reliability, riding comfort, energy consumption, noise, etc. The traction transmission system is the key technology of the elevator, the performance of which has direct influence on

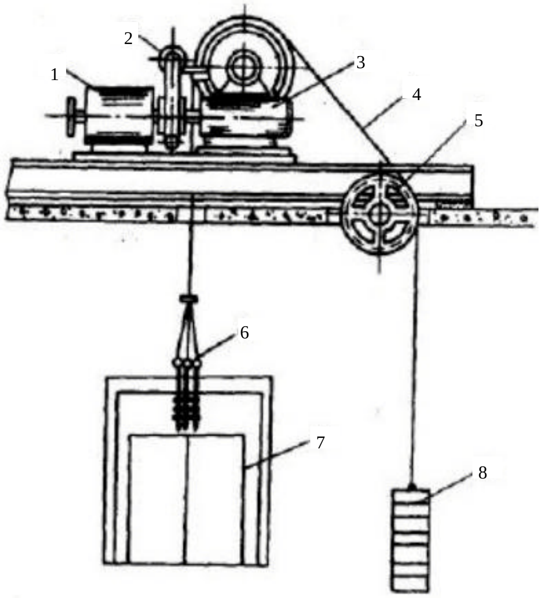

Fig. 1: Traction transmission system, (1) Motor, (2) Brake, (3) Gear reducer, (4) Hoisting rope, (5) Sheave, (6) Rope fastening, (7) Car and (8) Couter weight

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the start, brake, acceleration, deceleration, leveling accuracy and riding comfort, etc. Brake is an important device of the traction transmission system for its safety and reliability both of which are important factors that guarantee the running safety of the elevator. Although the existing electromagnetic brake has advantages of compact structure, convenient installation, powerful electromagnetic thrust, sensitive action, reliable braking and so on, there are still some key difficulties with the traction transmission device which should be investigated theoretically, such as rapid wear, high energy consumption, high noise, intensive vibration and impact and so on.

In addition, in the MRF transmission, the driving rotor and driven rotor are connected through MRF, so the impact and noise could be prevented. Besides, as the driving rotor and the driven rotor are not directly contacted, abrasion will be minor and energy consumption will be lower. Furthermore, the MRF Traction Transmission has other functions of infinitely variable speed, overload protection, etc. Because of these characteristics of the MRF traction transmission, many technical difficulties could be solved, such as fast wear, high energy consumption, high noise, intensive vibration and so on.

At present, Many relevant research works have been conducted on the design and performance analysis of MR torque transmission devices. FEM (finite element method) is used to analyzed magneto-rheological brake's characteristics in car, such as the magnetic circuit, fluid flow, heat transfer characteristics (Park *et al*., 2008). The relationship between speed and power for p = 85 w parallel disc type brake in different applied effect of the magnetic field is analyzed. Bica (2004) and Nam and Ahn (2009) designed a small steel roller of the brake and MR brake compared with traditional brake. Fuzhou University, Chen and Wei (2007) researched computational fluid dynamics method which based on electromagnetic rheological technology plane (clearance fixed) and corrugated surface (clearance change) double barrel type clutch performance. Whereas, there have not been any paper or literature on MRF elevator traction transmission or brake yet.

To design elevator traction transmission device based on MRF for a given specification, one must establish the relationship between the torque developed by MR fluids and the parameters of the structure and the magnetic field strength. In this study, the fundamental design method of the cylindrical MRF traction transmission device is investigated theoretically. A Bingham model is used to characterize the constitutive behavior of the MR fluids subject to an external magnetic field strength. Moreover, theoretical analysis, the equation of the torque transmitted by the MR fluid within the device is derived to provide the theoretical foundation in the MRF elevator traction transmission design of the device. Based on those equations, after mathematical manipulation, the calculations of the structure and width of the MRF elevator traction transmission are yielded.

OPERATIONAL PRINCIPLE

The MRF elevator traction transmission is a device to transmit torque and produce braking torque by the shear stress of MR fluid. The device has the property that their transmitting torque and braking torque change quickly in response to an external magnetic field strength. The operational principle of the cylindrical MRF elevator traction transmission is shown in Fig. 2. The MR fluid fills the working gap between the fixed outer cylinder and the rotor. The rotor rotates at a rotational speed of ω.

When the coil is not energized, the suspended particles of the MR fluid cannot restrict the relative motion between the fixed outer cylinder and the rotor. At this time only the off-field viscosity of the MR fluid is required to produce a very small brake torque.

However, in the process of operation, a magnetic flux path is formed when exciting current is put through the solenoidal coil. As a result, the MR particles gather to form many particle chains in the field direction. In the meantime, the mutual attraction between the adjacent particle chains leads to the formation of a columnar or reticular structure which presents a controllable yield stress. At this moment, the input plates and the brake plates are engaged and thereby the MR brake works in the loaded state. The transmitting torque and braking torque could be continuously adjusted by solely regulating the applied current. The values of

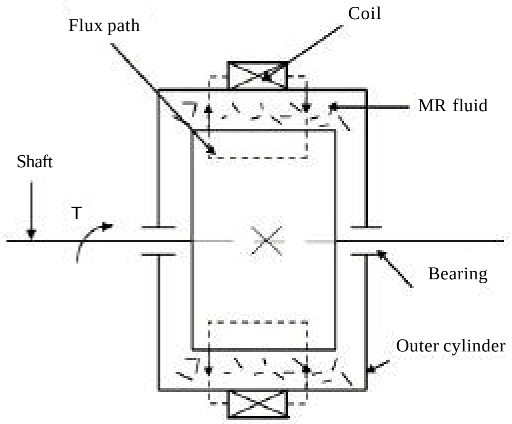

Fig. 2: Operational principle of the MR brake

transmitting torque and braking torque can be adjusted continuously by changing the external magnetic field strength (Huang *et al*., 1994).

DESIGN of MRF DEVICE

The traction elevator transfer power by friction between wire rope and groove. The elevator traction machine includes the steel wire rope, motor, reducer, traction wheel, MRF coupler and brake composition. According to the elevator running speed and load, motor and brake are chosen.

Comprehensive elevator traction drive system with the operational principle of the cylindrical MRF transmission, design a Fig. 4 for general arrangement diagram of MRF traction transmission device.

The device includes electro-magnetic adjusting speed motor, MRF coupler, reducer; sensor, MRF brake, Magnetizing Coil, MRF, runner; steel bar, dynamometer and so on. This device testing field strength and angular velocity can be detected braking torque. The size of the magnetic field intensity can be controlled excitation coil 6 which determine the transmitting torque and braking torque and the magnetic field strength of the relationship.

ANALYSIS MRF DEVICE

Analysis MRF coupler: The key question in the design of MRF elevator traction transmission is to establish the relationship between the torque and the parameters of the structure and the magnetic field strength.

In case that MRF is not under magnetic field, it behaves as Newtonian fluid. Under the magnetic field, it shows the Bingham characteristic which is expressed by equation (Carlson *et al*., 2001):

$$\left.\begin{array}{c}\tau = \tau_0(H)\mathrm{sgn}(\gamma) + \eta\gamma|\tau| \geq \tau_0(H) \\ \gamma^{\cdot} = 0|\tau| < \tau_0(H)\end{array}\right\} \tag{1}$$

In which, τ is the total shear stress of MRF, τ (H) is the shear stress due to magnetic field, η is the viscosity of MRF at zero magnetic field. H is the shear rate.

According to Ginder and Davis (1994), when MRF of magnetic solid particles have not reached complete saturation, MRF constitutive equation can be written as magnetic induction intensity power function form:

$$\tau_y(H) = \alpha B^{\beta} \tag{2}$$

where, α and β are MRF materials with the constants.

Figure 4 shows that the MRF coupler between active and passive pills movement.

As shown in Fig. 4, establish motion differential equations as follows:

$$\tau dx - (\tau + \frac{\partial \tau}{\partial y} dy)dx = 0 \tag{3}$$

Where shear stress:

$$\tau = -\eta \frac{du_x}{dy}$$

because MR fluid in the tangential velocity is much bigger than the radial velocity and axial velocity:

$$du = du_x = -\frac{\tau}{\eta} d_y \tag{4}$$

Solution differential of Eq. 4 as:

$$u(y) = -\frac{\tau}{\eta} y + c \tag{5}$$

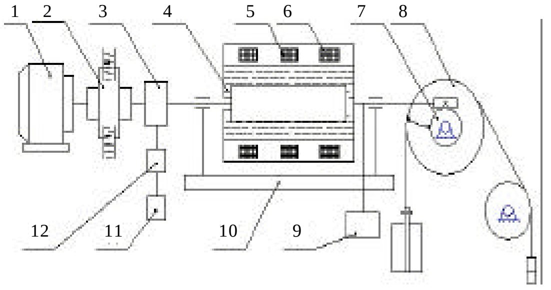

Fig. 3: Diagram of MR Traction Transmission Device, (1) Motor, (2) MRF coupler, (3) Sensor, (4) MRF, (5) MRF brake, (6) Coil, (7) Reducer, (8) Runner, (9) Iinstrument of magnetic field intensity (10) Support, (11) Velocimeter and (12) Torque measuring instrument

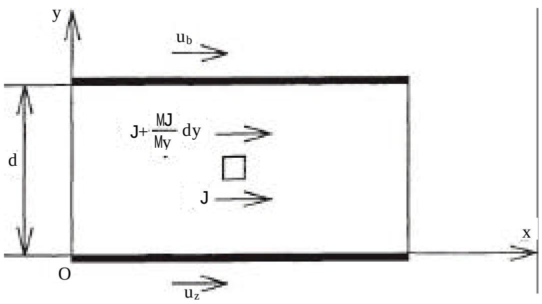

Fig. 4: MR fluid tangential section

By the boundary conditions $U(0) = U_Z$, $U(d) = U_b$, to yield:

$$\frac{\tau}{\eta} = \frac{u_z - u_b}{d} \tag{6}$$

By Eq. 5 and 6, to yield:

$$u(y) = \frac{-u_z + u_b}{d} y + u_2 \tag{7}$$

Equation 7 is velocity function of the MRF between active and passive pills.

As shown in Fig. 4, the radius of the MR fluid, take a micro circle, the area of $ds = 2\pi r dr$, the shear force of MR fluid for $dF = \tau\, ds$, the transmission of torque is:

$$dT = rdF = 2\pi\tau r^2\, dr \tag{8}$$

When the shear stress $|\tau| < \tau_0$, MR fluid between active and passive pills supplied for viscous shear torque:

$$T_1 = \int 2\pi\tau r^2 dr \tag{9}$$

As the radius of $u_z = r \bullet \omega_Z$, $u_b = r \bullet \omega_b$. The shear strain rate:

$$\dot{\gamma} = \frac{u_z - u_b}{d} = r \cdot \frac{\omega_z - \omega_b}{d} = \frac{r \cdot \Delta\Omega}{d} \tag{10}$$

According to Eq. 7, as:

$$\tau = -\eta \frac{du}{dy} = \eta \frac{u_z - u_b}{d} = \eta \frac{r \cdot \Delta\Omega}{d} \tag{11}$$

By Eq. 9 to yield:

$$T_1 = \int_{r_1}^{r_2} 2\pi\eta \frac{r \cdot \Delta\Omega}{d} r^2 dr = \pi\eta \frac{\Delta\Omega}{2d} \int_{r_1}^{r_2} 4r^3 dr = \pi\eta \frac{\Delta\Omega}{2d} (r_2^4 - r_1^4) \tag{12}$$

When the shear stress $|\tau| \geq \tau_0$ (H), By Eq. 1, 8 and 10 can be calculated by:

$$\begin{aligned} T &= \int 2\pi(\tau_0 + \eta \frac{r\Delta\Omega}{d}) r^2 dr = \int_{r_1}^{r_2} 2\pi\tau_0 r^2 dr + \\ &= \int_{r_1}^{r_2} 2\pi\eta \frac{\Delta\Omega}{d} r^3 dr = \frac{2}{3}\pi\tau_0 (r_2^3 - r_1^3) + \frac{\pi\eta\Delta\Omega}{2d}(r_2^4 - r_1^4) \end{aligned} \tag{13}$$

By Eq. 13, it can be saw that on MRF coupler transfer torque by consists of two parts: The torque generated by the yield stress and the torque generated MRF viscosity surface friction.

By Eq. 2 and 13 to yield:

$$T = \frac{2}{3}\pi\alpha H^n (r_2^3 - r_1^3) + \frac{\pi\eta\Delta\Omega}{2d}(r_2^4 - r_1^4) \tag{14}$$

Based on the relationship between magnetic field intensity and plus exciting current H = CI.

By Eq. 14 to yield:

$$T = \frac{2}{3}\pi\alpha (CI)^n (r_2^3 - r_1^3) + \frac{\pi\eta\Delta\Omega}{2d}(r_2^4 - r_1^4) \tag{15}$$

Based on this equation, MRF yield stress generates the torque that changes by the exciting current which is part of MRF coupler's adjustable transfer torque. MRF viscosity generates the torque which has nothing to do with plus a magnetic field changes, only depends on MRF viscosity, MRF thickness control device of transmission clearance and input/output speed.

Analysis of MRF brake: As shown in Fig. 5, r1 and r2 were cylindrical inner barrel and fixed outer cylinder radius, between them full of MRF, when the cylindrical inner barrel with angular velocity ω rotation, magneto-rheological fluid by shearing action and with angular velocity ω (r) rotation.

The shear rate can be calculated as follows (Yalcintas, 1999):

$$\gamma = -r \frac{d\omega(r)}{dr} \tag{16}$$

where, ω_r is the rotational speed in the MR fluid at radius r.

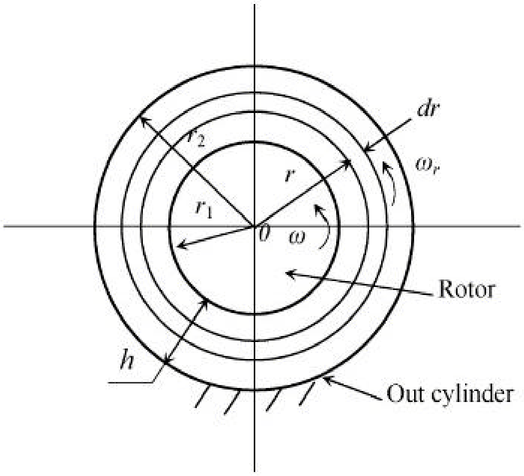

Fig. 5: Analysis of the torque

MR fluid in two cylinder intercropping circumferential flow of torque equation can approximatively expressed as:

$$\frac{d\tau_{r\theta}}{dr}+\frac{2\tau_{r\theta}}{r}=0 \tag{17}$$

where, $d\tau_{r\theta}$ is MRF circumferential flow produced by the shear stress, $d\tau_{r\theta}/dr$ is MRF shear stress along radius direction gradient.

Solution differential of Eq. 17 as:

$$\tau_{r\theta}=\frac{C_1}{r^2} \tag{18}$$

where, C_1 is integral constant.

By Eq. 16 and 18 can be given by:

$$\frac{C_1}{r^2}=\tau_y(H)-\eta r\frac{d\omega(r)}{dr} \tag{19}$$

Equation 16 and 19 can be further manipulated to yield:

$$\omega(r)=\frac{\tau_y(H)}{\eta}\ln r+\frac{C_1}{2\eta r^2}+C_2 \tag{20}$$

where, C_2 is integral constant.

When the cylinder MRF were viscous flow, the velocity boundary condition for:

$$r=R_1,\ \omega(r)=\omega,\ r=R_2,\ \omega(r)=0 \tag{21}$$

Then put Eq. 8 substitution Eq. 7 can get two integral constant, respectively:

$$C_1=\frac{2\eta R_1^2R_2^2}{R_2^2-R_1^2}(\frac{\tau_y(H)}{\eta}\ln(\frac{R_2}{R_1})+\omega) \tag{22}$$

$$C_2=-\frac{\tau_H}{\eta}\ln R_2-\frac{R_1^2}{R_2^2-R_1^2}(\frac{\tau_y(H)}{\eta}\ln(\frac{R_2}{R_1})+\omega) \tag{23}$$

Put Eq. 22-23 substitution Eq. 21 can get two integral constant, respectively:

$$\omega(r)=\frac{\tau_y(H)}{\eta}\ln r+\frac{R_1^2}{R_2^2-R_1^2}[(\frac{R_2^2-r^2}{R_2^2r^2})(\omega-\frac{\tau_y(H)}{\eta}\ln R_1)+(\frac{r^2-R_1^2}{R_1^2r^2})(-\frac{\tau_y(H)}{\eta}\ln R_2) \tag{24}$$

The braking torque T developed by the MR fluid can be calculated, to yield:

$$T_1=\frac{4\pi L_eR_1^2R_2^2\ln(\frac{R_2}{R_1})}{R_2^2-R_1^2}\tau_y(H)+\frac{4\pi L_eR_1^2R_2^2\omega}{R_2^2-R_1^2}\eta \tag{25}$$

As shown in Fig. 3 shows, Le has not occurred for MRF effect of the magneto-rheological fluid along the axial direction of the length, the MRF can't produce magnetic rheological effect but only happened viscous flow, its viscosity produce resistance torque T2 as follow:

$$T_2=\frac{4\pi L_eR_1^2R_2^2\omega}{R_2^2-R_1^2}\eta \tag{26}$$

By Eq. 25 and 26 can get MRF brake produce the total braking torque $T = T_1+ T_2$, to yield:

$$T=\frac{4\pi L_eR_1^2R_2^2\ln(\frac{R_2}{R_1})}{R_2^2-R_1^2}\tau_y(H)+\frac{4\pi(L_e+L_1)R_1^2R_2^2\omega}{R_2^2-R_1^2}\eta \tag{27}$$

SIMULATION OF MRF DEVICE

Simulation of MRF coupler: According to the MRF coupler torque mathematical model, to establish the related module simulation diagram. On MRF coupler torque model simulation, changing the input control magnetic field and size parameters can adjust magnetic rheological elevator transmission torque.

This simulation study used Chongqing instrument material research institute configuration model for MRF-J of the MR fluid. According to (Bai *et al*., 2010), fitting MRF magnetic induction intensity and the relationship between shear stress:

$$\tau_y(H)=0.024B^{1.785}$$

When the elevator operate stable, the speed of the differential $\Delta\Omega = 0$, the other MRF coupler's main parameters is listed in Table 1.

This design use multiple plate structure, MR device of total torque consist of the six same thickness superposition of MRF. The relationship between torque and exciting current are already shown in Fig. 6.

As shown in Fig. 6, torque is increasing by exciting current before to magnetic saturation. As one can see, the maximum transmission torque of design is about 50 N.m. By the torque T = 9550 P/n of the elevator motor, the transmission torque of design is satisfied the specified load 1000 kg of elevator.

Simulation of MRF brake: The total Brake torque expressions Eq. 27 show that the increase of the radius of brake wheel R_2, can make the brake obtain larger braking

Table 1 MRF coupler parameters

r_2	r_1	α	n
200 mm	195 mm	0.024	1.785

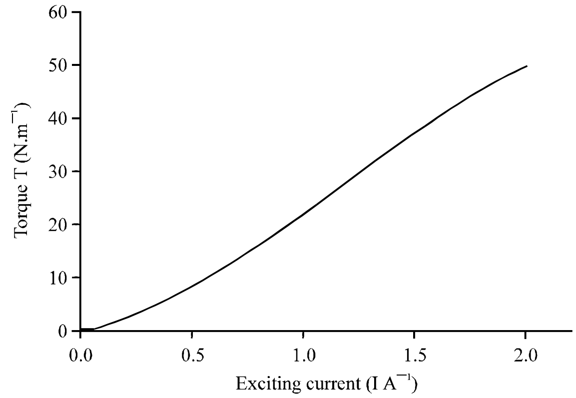

Fig. 6: Relationship between torque and exciting current

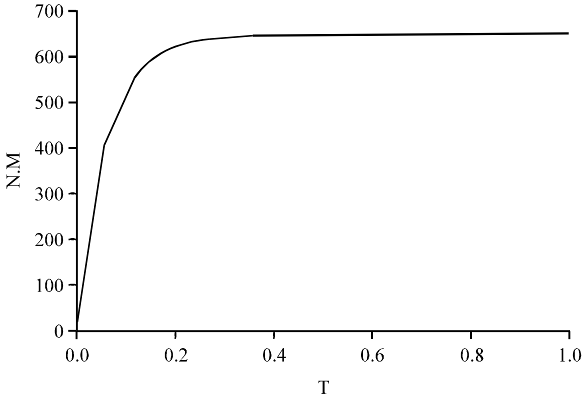

Fig. 7: MRF braking torque of curve

Table 2 brake simulation parameters

R_2/R_1	L_e/L_1	ω	B	η
200/195 mm	40/40 mm	1440 r min^{-1}	0-1T	0.09563 Pa.S

torque but considering the elevator traction system actual braking torque requirements, this paper design of MRF brake size R_2 as 200 mm, its main structure, control parameters listed in Table 2.

According to Eq. 25 and 26, by testing field strength and angular velocity can detect braking torque. The size of the magnetic field intensity can be controlled excitation coil.

According to the MR brake torque mathematical model, used MATLAB/Simulink to establish the related module simulation diagram as shown in Fig. 5. On MRF brake torque model simulation, changing the input control magnetic field and size parameters can adjust magnetic rheological elevator brake output braking torque.

Figure 7 shows that with the increase of the magnetic field intensity, MRF brake of torque increase significantly. At the same time change R_1 and R_2 value, can make the braking torque change. Therefore, through the above various factors balance can get good performance, brake torque to meet the requirements of elevator MRF brake.

By Eq. 27, the MR material in MRF traction transmission device should meet the requirements that the yield stress should be over 45 kPa, the influence of temperature on MRF little, the braking response time less than 0.5 sec and the zero-field viscosity low.

Obviously, it is proved that the design of the MRF traction transmission satisfied the braking torque requirements for the car descending to the lowest station nearby under 125% of the rated load required by the European standards EN81: 1993 Safety rules for the construction and installation of electric lifts (Chinese National Standard GB7588 Safety Norms for installation and Manufacturing of Elevators) in the most severe condition. It certifies that the appropriateness of the experimental data is sufficiently.

CONCLUSION

Basis on the above studies and analysis, the conclusions could be drawn as follows:

- The yield stress be over 45 kpa, the influence of temperature on MRF little, the braking response time less than 0.5 sec and the zero-field viscosity low of magneto-rheological material can meet MRF traction transmission device requirements
- MRF traction transmission device designed in this paper can meet the demand of torque transmission and maximum brake torque. Furthermore, in case of working safety of elevators, reserve allowance of brake torque is required
- It is proved that MRF transmission device is applicable to the elevator traction transmission system by building computation model and analyzing the rheological properties and brake torque
- The built mathematical model can explain the performance of MR device and the change law between torque and the electromagnetic field so as to lay a solid foundation for the optimization design of MRF traction transmission with higher speed and higher requirements

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