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A Review of the Application of Magnetorheological Fluid Technology in Drive-by-Wire Systems for New Energy Vehicles

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Abstract: In today's automotive industry, new energy vehicles are gradually evolving from traditional mechanical structures towards electrification, intelligence, and drive-by-wire systems. Mechanical steering systems, in this evolution, are increasingly revealing problems such as structural complexity, low integration, and insufficient safety. Magnetorheological fluids (MRFs), due to their millisecond-level response speed, continuously adjustable damping, and low energy consumption, are considered by many researchers to have broad application prospects in this field. This paper reviews relevant domestic and international literature, focusing on the current development status, material composition, working principle in systems, rheological properties, and application of magnetorheological actuators in drive-by-wire systems. It also emphasizes the design of actuator structures, road feel simulation technology to overcome feedback loss, and the current development status of intelligent control strategies. The paper summarizes the challenges facing the industrialization of magnetorheological technology in this sector and looks forward to future development directions. Ultimately, the study concludes that with the continuous maturation and improvement of smart materials, control algorithms, and chassis domain control technology, this technology will play a crucial role in future new energy vehicle chassis, providing new technological pathways for future development.

Keywords: Magnetorheological fluid; Steer-by-wire; New energy vehicles; Intelligent chassis; Magnetorheological actuator.

1. Introduction

In today's rapidly developing technological world, technological iteration is ubiquitous. Traditional technologies are increasingly unable to keep up with the demands of the new era, while new technologies must step up and become the new carriers driving industrial progress. Thus, technological iteration is not only universal but also inevitable. In our automotive field, the same transformation is underway. Since the development of automobiles, traditional mechanical linkages, relying on their mature structure and reliability developed over a century, have been widely used in the steering systems of mass-market passenger vehicles. However, as the automotive industry transitions towards electrification, intelligence, and integration, traditional mechanical linkages have instead limited the improvement of driving experience and technology. The mechanical steering column not only runs through the entire front compartment, occupying interior space, but also poses a risk of intrusion into the passenger compartment during a collision. Its unchanging fixed connection method also completely restricts the optimization of chassis structures within the industry. However, directly removing the mechanical linkage would introduce new problems such as a lack of road feel feedback and system failure.

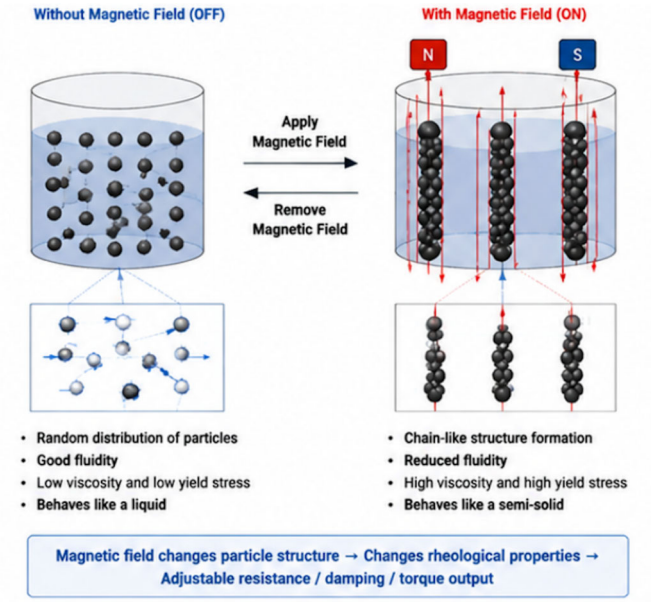


Figure 1. Working Principle of Magnetorheological (Fluid)

The emergence of the magnetorheological fluid (MRF), provides a new solution to this core problem. It can rapidly complete the reversible state transition between liquid and semi-solid states under the influence of a magnetic field, responding within milliseconds, and simultaneously continuously adjusting the damping force and output torque of the material. As shown in Figure 1, the working principle of magnetorheological fluids is based on the reversible rearrangement of magnetic particles under different magnetic field conditions, enabling rapid adjustment of mechanical properties.

This not only effectively improves the driver's perception of the road surface and helps enhance the overall handling stability of the vehicle, but also significantly improves the safety factor. Structurally, the introduction of magnetorheological technology means that in new vehicle designs, the chassis space is increased, and the architecture can be further optimized: most of the chassis space occupied by traditional gear sets and hydraulic lines can be used elsewhere, improving chassis integration and, more importantly, reducing the overall energy consumption of the vehicle.

But in our discussion, we must also pay attention to the duality of this technology. Although magnetorheological fluids do have significant advantages over traditional mechanical linkages in many aspects, seemingly solving all the problems of modern automobiles, there are still many challenges before it can be mass-produced and popularized. For example, how can the materials be modified to meet the requirements of long-term operation in civilian vehicles? How can the actuator output sufficient feedback torque within a limited space? And how can the control strategy reproduce the most realistic driving feel? After the mechanical connection is removed from the drive-by-wire system, how can functional safety be guaranteed? These questions cover multiple fields such as materials science, mechanical design, and automatic control. However, existing research is mostly focused on a single direction and lacks a systematic overview of the integration of materials, actuators, control strategies, and the entire vehicle. In addition, details such as cost, lifespan calculations, and efficiency under complex operating conditions also need further research.

In this paper, I will review the application of magnetorheological technology in drive-by wire systems, especially focusing on the material properties of magnetorheological fluids, the design of actuator structures, the control strategies and fault safety guarantees of vehicles in new designs. Based on this, combined with the system integration of the whole vehicle, I will analyze the future development. This paper aims to provide a relatively complete reference for related research.

2. Basic Theory of Magnetorheological Fluids

2.1. Overview of the Development of Magnetorheological Fluids

Before we delve into the application of magnetorheological technology in drive-by wire systems, I believe it is necessary to understand the basic concepts of magnetorheological fluid (MRF) itself. It is a typical intelligent fluid that can quickly switch between liquid and semi-solid state under the action of external magnetic field. It has a fast response speed, continuously adjustable damping force, and high precision. For the above reasons, it has gradually become an important research object in the control system of new energy vehicles[1].

Magnetorheological fluid was first proposed by American scholar Jacob Rabinow in the 1940s, but due to the limitations of material performance, electromagnetic control and manufacturing process precision, it was only at the experimental research stage at that time. In recent years, with the discovery of permanent magnet materials and the development of power electronics and control technology, the stability and responsiveness of manufactured magnetorheological fluids have been continuously improved, and they have gradually reached the conditions for engineering application[2].

As new energy vehicles begin to develop towards electrification, intelligence and drive-by-wire, traditional mechanical linkages have gradually become a constraint in chassis design. Compared with traditional linkage schemes, the new magnetorheological actuator can reduce energy consumption while ensuring fast response, and even improve the consistency of road feel feedback. These advantages have also made it widely concerned in the fields of drive-by-wire steering, braking and suspension[1].

Now, a relatively mature development path has been formed abroad. The newly developed motor-magnetorheological brake hybrid actuator of INVENTUS Development GmbH is the first to combine active drive and damping control into the same mechanism, thereby realizing the miniaturization and high efficiency of the actuator [3][4]. At the same time, in China, the magnetorheological road feel simulator proposed by Nanjing University of Aeronautics and Astronautics adopts an unprecedented three-coil independent excitation structure, which realizes road feel simulation and also has functions such as automatic return and fault protection, which also promotes the practical application of magnetorheological technology in drive-by wire systems [5][6].

At the macro level, the research on magnetorheological fluid has transformed from simple material research to actuator design, control algorithm and whole vehicle system integration, which is more practical and in line with reality. It has also gradually become an important technical basis for the design of intelligent chassis for new energy vehicles [1][5].

2.2. Composition and working principle of magnetorheological fluid

Magnetorheological fluid is mainly composed of magnetic particles, carrier fluid and additives. The magnetic particles are generally carbonyl iron powder, which is the core of forming magnetic chain structure; while the carrier fluid is usually silicone oil or mineral oil, which is used to ensure good flow performance; the additives are used to improve particle dispersion, prevent particle sedimentation and extend its service life [1][7].

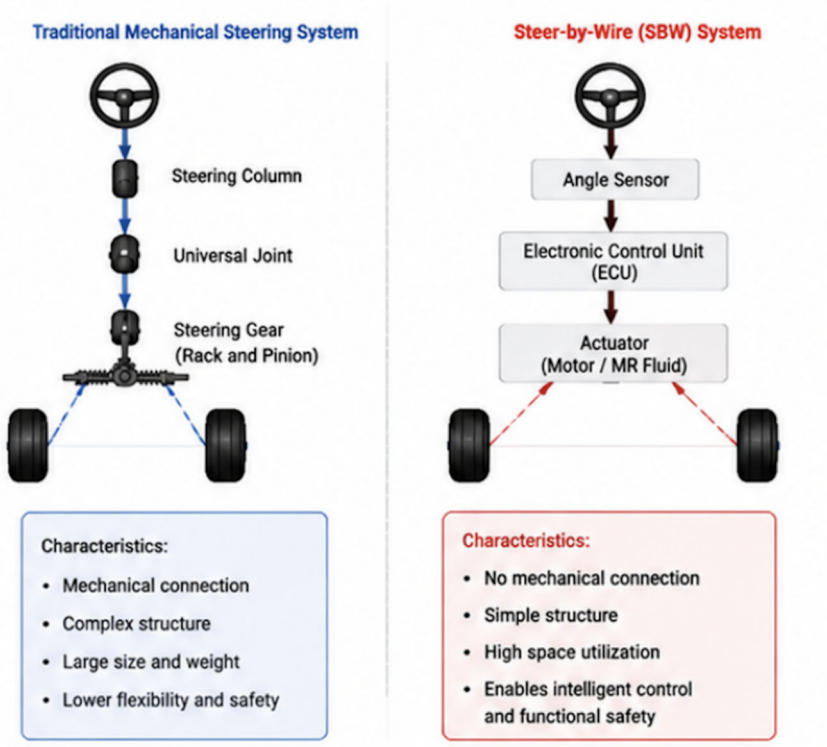


Figure 2. Comparison between Traditional Steering System and Steer-by-Wire (SBW) System

When no magnetic field is applied to the liquid, the magnetic particles are randomly distributed in the fluid, and the magnetorheological fluid behaves like an ordinary fluid; but when the external coil is energized, the particles quickly arrange themselves along the magnetic field direction to form a chain structure, which rapidly increases the yield stress and shear resistance of the fluid. As the excitation current increases, the output damping and torque also increase; conversely, after the magnetic field is removed, the particle chain will quickly disintegrate and the material will return to a liquid state, and the whole process can usually be completed within milliseconds. The fast response speed can meet the requirements of the wire control system for real-time control [1][2].

Nowadays, the Bingham model is usually used in engineering research to describe the mechanical properties and characteristics of magnetorheological fluids. However, in order to meet the higher precision requirements of new energy vehicles, researchers have recently introduced the Herschel–Bulkley model along with the microscopic model of the particle chain to improve the ability to predict and describe nonlinear behavior, thereby providing a new and solid theoretical foundation for the design and control algorithm of future actuators [1][8].

2.3. Rheological characteristics and performance advantages of magnetorheological fluid

Compared with traditional mechanical linkages or other solutions, the biggest advantage of magnetorheological fluid is that it has both fast response capability and continuously adjustable torque. It can adjust and transmit feedback torque in real time, which precisely meets the requirements of new energy vehicles for wire control systems to have high control accuracy and fast dynamic response.

As shown in Figure 2, compared with traditional mechanical and electric motor-based solutions, magnetorheological actuators provide advantages in response speed, controllability, and energy efficiency, making them suitable for intelligent chassis applications.

More research shows that the response time of high-performance, high-quality magnetorheological fluids is usually less than 10 ms, and after optimization of magnetic circuit and control algorithm, it can even reach the millisecond level. Therefore, it can complete the feedback output and complete the corresponding action at the moment the driver turns the steering wheel, which is of great significance for high-speed driving and emergency obstacle avoidance[1].

Compared with traditional hydraulic or pure electric motor solutions, magnetorheological actuators have more stable output, lower energy consumption, and a more compact structure. The motor-magnetorheological hybrid actuator proposed by Wilhelm et al. mainly uses the motor to drive actively, while the magnetorheological brake is responsible for the damping adjustment. While increasing the feedback torque, it also significantly reduces the energy consumption of the entire system. This idea provides a new design concept for the lightweighting and high integration of new energy vehicles [3][4].

However, we still need to pay attention to the existing shortcomings. The current magnetorheological fluid still has problems such as high zero-field viscosity, particle sedimentation, temperature sensitivity and insufficient stability due to long-term use, and these factors will directly affect the life and control accuracy of the actuator. Therefore, further modification of materials, optimization of structure, and compensation control when working at different temperatures may become important research directions in this field in the next few years [1][7].

In summary, magnetorheological fluids, with their advantages of fast response, continuous adjustability, and low energy consumption, provide new technical solutions for the

development of drive-by-wire systems for new energy vehicles. In the future, with the continuous development of materials, actuators, and intelligent control technologies, magnetorheological technology may be expected to achieve technical breakthroughs in targeted areas such as drive-by-wire steering, braking, and intelligent chassis, and continue to develop towards the ideal direction of high reliability, integration, and intelligence [1][3].

3. Key Technologies of Magnetorheological Actuators in Drive-by-Wire Systems

3.1. Structural Design of Magnetorheological Actuators

The actuator is an important carrier connecting the magnetorheological fluid and the drive-by-wire system. Its structural design directly determines the output torque, response speed, and overall control performance of the entire system. Especially for new energy vehicles, the steering system of the drive-by-wire must provide stable and sufficient feedback torque within a limited installation space. Therefore, finding a way to reduce the size of the actuator, maintain low energy consumption, and still have high-density feedback torque and high reliability has become an important research direction.

According to the shearing mode and magnetic field distribution of magnetorheological fluid, the current design of magnetorheological actuators mainly includes cylindrical, disc and multi-pole composite structures. The manufacturing process of cylindrical actuators is the simplest and the magnetic circuit design is the most mature. It was the most widely used in the early stages. However, due to the very limited effective shearing area, the output torque is small, which makes it difficult to meet the requirements of new energy vehicles for high-performance drive-by-wire systems [1]. The disc structure increases the utilization rate of magnetorheological fluid per unit volume by increasing the shearing radius, obtains a larger output torque, has a smaller axial dimension, and is easier to install. However, the magnetic field distribution is still somewhat uneven at this stage, and the design needs to be optimized again [7].

In recent years, multi-pole magnetic circuit design has gradually become a new research hotspot. Compared with the traditional single-pole structure, the multi-pole magnetic circuit can utilize more magnetic field areas, improve utilization rate, shorten path, and thus improve the speed of transmission output torque and response, which provides a new idea for the research and development of steering actuators. [7].

In addition to single magnetorheological actuators, hybrid actuators are also attracting attention. The integrated output shaft proposed by Wilhelm mentioned above achieves a combination of fast response and high torque output [3][4]. Experimental results show that this scheme can output a torque of about 25 N·m while controlling the working power to only about 60 W, which is about 83.3% lower than the energy consumption of the traditional pure motor scheme (450W), reducing the long-term load on the motor and thus improving the reliability of the actuator [3].

In China, the three-coil independent excitation magnetorheological road feel simulator scheme of Nanjing University of Aeronautics and Astronautics mentioned above integrates road feel simulation, automatic return, and fault protection, which improves control accuracy and system integration, and also provides a new potential scheme for the research and development of steer-by-wire [6]. In general, magnetorheological actuators are transforming from a single braking structure to a comprehensive structure integrating motor drive, magnetorheological fluid regulation, and intelligent control. Multifunctionality provides an important foundation for the development of intelligent chassis [1][5].

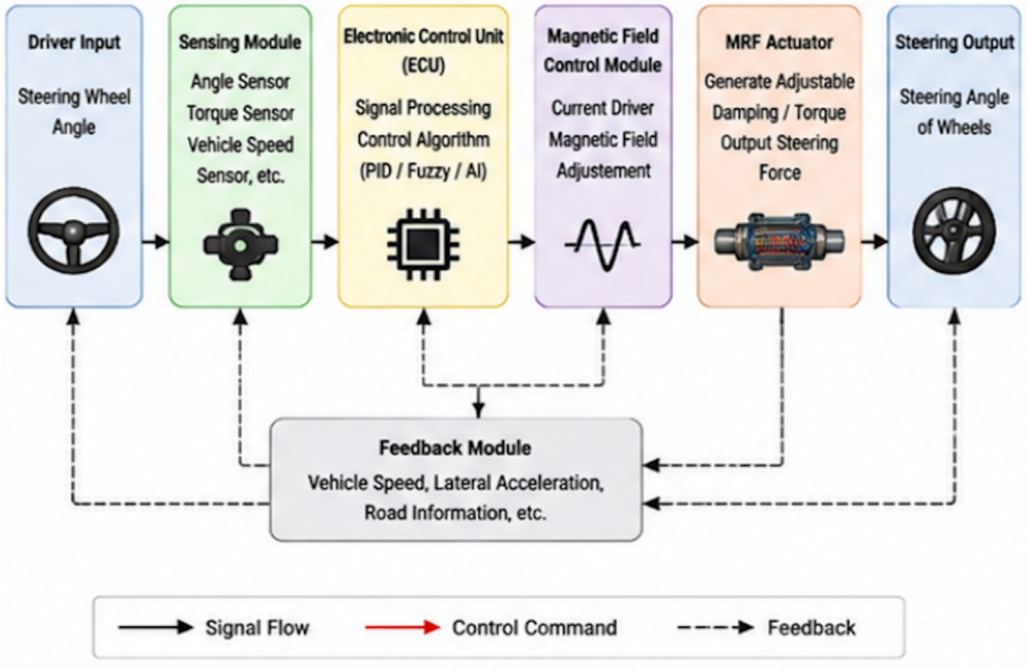


Figure 3. Control Architecture of MRF Actuator in Steer-by-Wire System

3.2. Magnetorheological road feel simulation technology

In the Steer-by-Wire (SBW) system, because the traditional mechanical steering column is gradually being replaced by electronic and "intelligent" control systems, the driver cannot directly obtain feedback from the road surface through the mechanical structure. Therefore, how to reconstruct the real and stable road surface feedback in the new system has become an important issue for the popularization of the steer-by-wire system [1][5].

Currently, there are three main ways to simulate road feel: pure motor simulation, active damping simulation, and magnetorheological actuator simulation. The control accuracy of the pure motor scheme is relatively high compared with others, but it requires a large output to support it under high-speed working conditions, which easily leads to high energy consumption. The active damping scheme has a relatively simple structure, but the range of feedback torque provided is very limited, making it difficult to meet the needs of rapid real-time control in complex working environments [3]. In contrast, the magnetorheological actuator utilizes the continuously adjustable damping force of its own magnetorheological fluid, which can quickly adjust the provided feedback torque according to different vehicle states, making the feedback given by the steering wheel more similar to that of the traditional mechanical steering system.

When driving at low speed, the controller will reduce the excitation current, allowing the steering wheel to maintain a relatively light operating force; as the vehicle speed gradually increases, the system gradually increases the amount of excitation current, which will also increase the damping torque, and the steering wheel feedback will naturally become more stable. When the vehicle is driving on complex road conditions, such as wet and slippery roads, potholes, or emergency obstacle avoidance, the controller can also combine vehicle dynamics parameters such as vehicle speed, yaw rate, and tire lateral force to adjust the provided feedback torque in real time, improving the driver's perception of the vehicle under specific conditions, thereby improving the vehicle's safety factor [1][3].

3.3. Control Strategy and Fail-Safe Design

Magnetorheological actuators not only rely on structural design, but the control strategy also plays a crucial role in the overall performance of the system.

As shown in Figure 3, the complete MRF-based steer-by-wire system integrates driver input sensing, control algorithms, magnetic field adjustment, actuator response, and feedback torque generation.

At present, PID control is still the most widely used control method due to its simple structure and low cost. However, because magnetorheological fluid has obvious nonlinear characteristics, its yield stress will be affected by external factors such as magnetic field, temperature, and shear rate, which may lead to the problem of response lag and control accuracy reduction in traditional PID control under complex working conditions [1][8].

In order to further improve the performance of control, researchers are slowly trying to introduce intelligent control methods such as fuzzy control, adaptive control and model predictive control (MPC). Fuzzy control can directly adjust the amount of excitation current based on the real-time state of the vehicle, and has a high degree of adaptability to the nonlinear characteristics of magnetorheological fluid; adaptive control can intelligently and automatically control different parameters through vehicle load, tire state and road adhesion conditions to improve the stability of the system; finally, model predictive control combines the vehicle dynamics model and optimizes the feedback torque by predicting the future state of the vehicle. It has higher control accuracy than the former two in high-speed lane change, continuous curves and emergency obstacle avoidance. However, due to the large amount of computation, this method is still mainly in the laboratory research stage [5][8].

In addition to the control algorithm, functional safety is also a problem that must be solved in the practical application of magnetorheological drive-by-wire system in engineering. Under the premise of eliminating the traditional mechanical steering column, we need to ensure that the steering wheel has basic feedback capability when the system loses power or the controller fails. At present, the main considerations are backup power supply and permanent magnet retention as two safety solutions for failure. Backup power supply can continue to maintain the normal operation of the actuator for a certain period of time when the main system fails, but it increases the cost and weight of the whole vehicle; while permanent magnet retention scheme uses permanent magnet as a new technology to maintain the basic magnetic field. Even if the system loses power, the magnetorheological fluid can still provide a certain damping capability under the influence of Lorentz force, so that the steering wheel has the necessary feedback torque under extreme conditions. The structure is simple, the reliability is high, the energy consumption is low, and it is also in line with the development direction of lightweighting of new energy vehicles [3][5].

Overall, the control technology of magnetorheological actuators has gradually changed from traditional PID control to a system of collaborative control of multiple intelligent control algorithms. In the near future, with the advancement of artificial intelligence, vehicle dynamics modeling and intelligent chassis technology, the new era actuator with magnetorheology as the core will achieve closer collaboration in all aspects, which will also provide more reliable technical support for the steer-by-wire, brake-by-wire and intelligent chassis systems of new energy vehicles. Similarly, promoting the practical application of magnetorheological technology and making the technology more in line with the good prospects of industrial development [1][3][5].

4. Conclusion and Outlook

Nowadays, as new energy vehicles gradually develop towards electrification, intelligence, and chassis-by-wire control, traditional mechanical chassis are gradually being replaced by new electronic control systems. Consequently, steer-by-wire, brake-by-wire, and intelligent chassis are becoming important directions for future automotive development. In this context, magnetorheological fluids, with their millisecond-level response speed, continuously adjustable damping, high control precision, and low energy consumption, provide a new technological path for the future development of new energy vehicles.

This paper reviewed the application of magnetorheological technology in automotive steer-by-wire systems. It introduced the historical development of magnetorheological fluids, their composition, working principle, and rheological

properties, and analyzed their advantages compared with traditional mechanical and pure electric motor solutions. Furthermore, the structural design of magnetorheological actuators, road feel simulation technology, and control strategies within the system were discussed. Through the integration of optimized magnetic circuit design, improved actuator structures, and intelligent control algorithms, magnetorheological actuators have the potential to improve vehicle steering response speed and feedback torque. Under ideal conditions, this technology can also contribute to improving vehicle handling stability and driving experience while maintaining lightweight design and low energy consumption.

However, despite the significant progress achieved in magnetorheological technology, several challenges remain before large-scale industrial application can be realized. Issues such as material stability, actuator cost, temperature adaptability, long-term durability, and functional safety still require further improvement. Future development should focus on optimizing magnetorheological fluid formulations, enhancing particle dispersion stability, improving magnetic field utilization and torque density, and achieving more compact and lightweight actuator designs. Meanwhile, the combination of intelligent algorithms and advanced control strategies may further improve system accuracy, reliability, and safety.

In conclusion, magnetorheological technology represents a promising direction for the future development of intelligent chassis systems. With continuous advancements in material science, actuator design, and intelligent control technology, magnetorheological actuators are expected to play an increasingly important role in automotive drive-by-wire systems. Ultimately, this technology may contribute to the development of new energy vehicles with higher safety, reliability, intelligence, and driving performance.

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