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A Review of Research on Electromagnetic Suspension Technology for New Energy Vehicles

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Abstract

Driven by the global "double carbon" goal and the transformation of the automobile industry towards electrification and intelligence, the chassis system of new energy vehicles has changed from achieving a "balance of handling smoothness and stability" to meeting the needs of "good driving performance, intelligence, and high energy utilization". Relying on its core advantages such as fast response speed, wide adjustable damping range, and high energy recovery efficiency, electromagnetic suspension has become a key technology to resolve the contradiction between long endurance and high performance of new energy vehicles. This paper conducts a systematic review of the domestic and foreign research progress of electromagnetic suspension technology for new energy vehicles, explores its structural types, performance optimization and control strategies, and quantitatively analyzes the impact of structural characteristics on the transmission efficiency and spatial compatibility of different topological configurations; analyzes the key approaches to performance optimization from the three dimensions of electromagnetic characteristics, mechanical characteristics, and thermal characteristics; and compares the control effects and engineering applicability of classic control, modern control, and intelligent control strategies. Finally, the shortcomings of the current technology are clarified, and the future development of related fields is prospected, with a view to providing reference for the technological innovation and industrial application of electromagnetic suspension for new energy vehicles.

Keywords

New Energy Vehicles; Electromagnetic Suspension; Structural Design; Performance Optimization; Energy Recovery.

1. Introduction

Since 1989 when Karnopp proposed the idea of using permanent magnet motors as variable damping dampers, after decades of development, electromagnetic suspension technology has formed two mainstream structures: rotating and linear [1]. It has achieved remarkable results in terms of control strategies and performance optimization. However, new tests are coming one after another: First, because the battery pack adopts an integrated installation method, the chassis space becomes narrow, which places higher requirements on the miniaturization and lightweight of the suspension structure. The volume and mass of traditional electromagnetic suspension have increased compared with passive suspension. This has an impact on the optimization of non-sprung mass; secondly, taking into account the cruising range, the suspension is required to recover as much energy generated by vibration as possible while ensuring dynamic performance. However, the actual feedback energy efficiency of electromagnetic suspension is currently. After decades of development, electromagnetic

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suspension technology has formed two mainstream structures: rotary and linear. Remarkable results have been achieved in terms of control strategies, performance optimization, etc., but new tests are coming one after another: First, due to the battery pack. The efficiency is obviously affected by road conditions and vehicle speed; thirdly, intelligent driving scenarios require the suspension to respond quickly and adapt to a variety of working conditions. Traditional control strategies are difficult to cope with the collaborative optimization of dynamic performance and energy feedback efficiency under complex road conditions.

2. Electromagnetic Suspension Structure and Classification

The rotary electromagnetic suspension uses a motion conversion device to convert the vertical reciprocating motion of the suspension into the rotational motion of the motor to achieve the purpose of energy recovery and damping force adjustment. Its core part is composed of three parts: a rotating motor, a motion conversion device and an energy feeding circuit. According to the differences in the motion conversion device, it can be further subdivided into three different subtypes: ball screw type, rack and pinion type and rocker arm type.

2.1 Rotating Electromagnetic Suspension

The rotary electromagnetic suspension uses a motion conversion device to convert the vertical reciprocating motion of the suspension into the rotational motion of the motor to achieve the purpose of energy recovery and damping force adjustment. Its core part is composed of three parts: a rotating motor, a motion conversion device and an energy feeding circuit. According to the differences in the motion conversion device, it can be further subdivided into three different subtypes: ball screw type, rack and pinion type and rocker arm type.

2.1.1 Ball Screw Electromagnetic Suspension

Among today's rotary electromagnetic suspensions, the ball screw type is the mainstream configuration. Its key advantages are that the transmission efficiency is at a high level, the motion has good smoothness, and it can effectively reduce mechanical losses. Bose uses a combination of dual-motor symmetrical arrangement and ball screws, by controlling the dual motors to output torque of the same size and opposite direction, so as to eliminate the torsional vibration problem caused by the reverse torque, the results of the actual vehicle test show that this suspension can reduce the steering roll angle by more than 40%, and the degree of fluctuation of body attitude when passing speed bumps is reduced by 50%. The ball screw electromagnetic suspension, which is the result of ZF and Volkswagen Group's joint research and development work, uses the arrangement of upper and lower springs to effectively avoid the damage caused by inertial shock to the suspension system, and the 12 V power supply system is equipped with a lower energy consumption than the hydraulic active suspension, but the mass is increased by about 15 kg compared to the conventional passive suspension.

The ball screw feed suspension designed by Liu Songshan's team of Jilin University places the motor above the fenders, which greatly reduces the space occupied by the chassis, and relies on the traditional linear small damping and feed nonlinear damping for parallel design, so that the motor power is reduced [2].

The main advantage of this configuration is that the technology is highly mature and the energy recovery efficiency is relatively stable, which is suitable for mainstream new energy vehicle types such as cars and SUVs.

2.1.2 Rack and Pinion Electromagnetic Suspension

The rack and pinion electromagnetic suspension uses the rack and pinion mechanism to achieve the conversion of motion, and its structural characteristics are that the space requirements are small when arranged horizontally, and it is suitable for application in new energy vehicle models with a relatively cramped chassis space, such as wheel-side motor drive, the combat vehicle electromagnetic suspension jointly developed by the University of Texas and the Department of Defense, using the rack and pinion mechanism, the single-wheel bench test shows that under off-road conditions, the

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root mean square value of the body acceleration of the suspension is lower than that of the passive suspension [3]. Its transmission efficiency is lower than that of ball screw.

The rack and pinion electromagnetic suspension developed by Zuo Lei's team at the State University of New York at Stony Brook innovatively introduced a device called "mechanical motion rectifier" (two-way clutch), which allows the motor to always maintain a one-way rotation state to avoid energy loss caused by the commutation of the power generation voltage, and the actual vehicle test results show that at a speed of 15 mph, the average recovery power of the suspension can reach 15.4 W, compared with the absence of a rectifier structure, which is 40% higher, however, The noise problem caused by gear meshing is more prominent, and the noise value reaches 65 dB when the vehicle is driving at high speed, which is 10~15 dB higher than that of ball screw suspension.

2.1.3 Rocker Arm Electromagnetic Suspension

The rocker arm electromagnetic suspension uses the rocker arm and push rod to transmit the movement of the suspension to the motor to achieve the integrated arrangement of the actuator and the body, which meets the integrated design needs of the intelligent chassis, and the "eROT" rocker electromagnetic suspension lever actuator developed by Audi is integrated into the subframe beam, and the average feedback power of each suspension is in the range of 100~150 W, and on the road of secondary roughness, its maximum feedback power reaches 613 W, which can reduce carbon dioxide emissions per kilometer by 3 g. Its subsequent AI suspension uses harmonic gear reducers to achieve the effect of deceleration and increase torque, with a transmission ratio of 80, which can maintain smoothness under complex working conditions, but its structure is relatively complex, and the cost is higher than that of traditional electromagnetic suspension.

Yin Jun's Tongji University team proposed a rocker arm electromagnetic feed suspension based on double wishbone suspension, which completed the construction of the test bench with the help of the design of the gear reducer, and was equipped with a μ comprehensive robust controller, which could reduce the acceleration of the mass on the spring.

2.2 Linear Electromagnetic Suspension

Linear electromagnetic suspension does not require a motion conversion mechanism to directly generate electromagnetic force and electrical energy by relative motion between the stator and the mover. It has some significant advantages, such as extremely fast response speed, can reach milliseconds and no mechanical transmission loss, and can be divided into three categories according to the topological configuration, namely cylindrical, flat and U-shaped, among which the cylindrical shape has become the main choice of new energy vehicles due to its high space utilization.

The Czech University of Technology uses a three-phase synchronous linear motor manufactured by Copley Controls TBX3810 uses a robust control algorithm to design the electromagnetic actuator, and the damping response time is only 5 ms, which is less than that of the rotary suspension, while the cylindrical electromagnetic suspension jointly developed by Eindhoven University of Technology in collaboration with SKF and BMW uses harmonic modeling to optimize the magnetic pole configuration to achieve a size similar to that of the traditional passive shock absorber [4]. The fieldless damping characteristics of the suspension can provide basic vibration damping capabilities in the event of actuator failure, and the ride comfort has been significantly improved through vehicle tests.

The cylindrical linear electromagnetic suspension prototype developed by the Yu Fan team of Shanghai Jiao Tong University uses the design scheme of permanent magnet synchronous motor. The prototype has high power density of 2.5 kW/kg, and its energy recovery is confirmed by bench tests, and its energy feed efficiency is improved compared with that of rotary suspension, but the end effect of linear motor causes the magnetic field to be nonlinear, and complex control algorithms are needed to compensate for the fluctuation of damping force.

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Table 1. Comparison table of electromagnetic suspension with different structures

Types of structures	Response time	Space compatibility	Cost	Vehicle type	Pros and cons
Ball screw type	10~15 ms	Medium	Medium	Sedans, SUVs	Advantages: mature technology, high transmission efficiency; Disadvantages: Insufficient high-frequency attenuation, mechanical clearance affects accuracy
rack and pinion type	8~12 ms	Good	Medium low	Wheel-side motors drive models	Advantages: small lateral space occupation; Disadvantages: low transmission efficiency and large meshing noise
Rocker arm type	12~18 ms	Excellent	High	High-end intelligent new energy vehicles	Advantages: high degree of integration, high feed efficiency; Disadvantages: complex structure and high cost
Cylindrical linear type	3~5 ms	Medium	High	High-performance new energy vehicles	Advantages: fast response speed, no transmission loss; Disadvantages: obvious end effect, large fluctuation of damping force

As is shown on Table. 1, it is concluded that the linear electromagnetic suspension shows obvious advantages in terms of response speed and energy recovery efficiency, but its cost is relatively high and the end effect makes the control quite complicated. The comprehensive performance of the ball screw type is the most outstanding, which can be used as a priority for the current implementation of industrialization, while the rocker arm type is more in line with the integration needs of future intelligent chassis.

3. Optimization of Electromagnetic Suspension Performance

The core purpose of the performance optimization of the electromagnetic suspension of new energy vehicles is to achieve the balance of "high thrust density, low energy loss, and strong thermal stability".

3.1 Optimization of Electromagnetic Characteristics

The key to optimizing electromagnetic characteristics is to improve the thrust density and energy conversion efficiency, and reduce electromagnetic losses, which are mainly realized through three ways: motor topology design, magnetic pole array optimization and winding parameter matching.

In the field of topology design, in view of the simple structure, low cost, and high temperature resistance of linear switching reluctance motors (LSRAs), which have become a key alternative for electromagnetic suspension of new energy vehicles, the four-phase dual-sided LSRA designed by Lin et al. uses the construction form of four parallel modules to share axes, and the peak thrust reaches 2000N and the continuous thrust is 500N, and the volume is controlled in the range of 300 mm×300 mm×600 mm to meet the needs of medium-sized new energy vehicles [5]. In contrast, the permanent magnet synchronous linear motor (LPMSM) has a higher thrust density and small thrust ripple, but the NdFeB permanent magnet has the risk of high-temperature demagnetization and is more expensive than LSRA.

Halbach arrays are a key technology for improving electromagnetic performance due to their ability to enhance the strength of the magnetic field on one side. The research results of Zhu et al. show that the single and double-layer Halbach arrays can improve the energy recovery power of linear motors, but the complexity of their manufacturing has also increased significantly.

In the field of winding parameter matching, Wei et al. used Ansys/Maxwell to simulate and analyzed the arrangement of different coils and permanent magnet arrays, and found that when the three-coil arrangement scheme was adopted, the attenuation rate of the main power reached the lowest degree and the stability reached the best level [6].

3.2 Optimization of Mechanical Properties

In the field of transmission loss optimization, the lead and thread accuracy of the ball screw will directly affect the transmission efficiency, the research carried out by Liu Songshan's team shows that when the lead of the ball screw is 6 mm, its transmission efficiency is higher than that of the lead of 4 mm, but its damping adjustable range is reduced, this situation needs to be achieved with the help of the lead and motor related parameters to achieve the balance of the two, for rack and pinion suspension, the helical gear is used to replace the spur gear, the meshing loss is reduced, But it also increases the cost of processing.

In the field of structural stiffness optimization, Yin Jun's team from Tongji University took the rocker arm electromagnetic suspension as the research object and used the topology optimization method to design the rocker arm structure, and the stiffness of the optimized rocker arm structure was significantly improved, and its mass was also reduced, and the optimization results were remarkable, alleviating the problem of smoothness deterioration caused by the increase of non-sprung mass. Yu Fan's team at Shanghai Jiao Tong University used a carbon fiber composite shell in the linear electromagnetic suspension, which reduces the mass of the suspension and increases the rigidity compared to the aluminum alloy shell, but the problem is the increase in cost.

In terms of suppressing the influence of inertial mass, Liu Songshan et al. conducted research and found that the inertial mass of electromagnetic suspension can advance the resonance frequency of the suspension by 5 to 10 Hz, which in turn worsens the smoothness of the wheel resonance area.

3.3 Optimization of Thermal Characteristics

The thermal characteristics of the electromagnetic suspension of new energy vehicles will have a direct impact on its stability during long-term operation, especially in the continuous bumpy road conditions, the temperature rise of the motor is very likely to cause problems such as permanent magnet demagnetization and winding insulation aging.

The use of permanent magnet materials with high temperature resistance can increase the upper limit of the working temperature of the motor from 150 °C to 250 °C, but the cost will increase by about 2~3 times compared with NdFeB permanent magnets.

Table 2. Comparison of performance optimization methods

Optimize dimensions	approaches	Optimize results	Applicable scenarios	Limitations
Electromagnetic properties	Halbach array + winding optimization	Thrust density increased	High-performance new energy vehicles	The manufacturing complexity is high, and the magnetic pole processing error affects the performance
Mechanical properties	Lightweight materials + topology optimization	Reduced inertial mass	mainstream new energy cars and SUVs	Carbon fiber and other materials have high costs and high processing process requirements
Thermal characteristics	Liquid cooling system + thermal management control	The temperature rise decreases	Drive new energy vehicles over long distances	The liquid cooling system increases the volume and quality, and the control algorithm is highly complex

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As is shown on Table. 2, in terms of the balance between optimization effect and cost, the optimization of mechanical properties has the highest cost performance and can be used as the priority choice of current industrialization. Although the optimization of electromagnetic characteristics can significantly improve performance, its cost is relatively high, and it is more suitable for high-end vehicles; The optimization of thermal characteristics is mainly for long-distance driving scenarios, which is the key to solving the durability problem of electromagnetic suspension.

4. Result

4.1 Structural and Dynamic Results

Among the rotary electromagnetic suspension, the ball screw transmission efficiency is the highest, and the actual vehicle can reduce the steering roll angle by more than 40% and the body attitude fluctuation by 50%, but the mass of a single set is increased by about 15 kg compared with the traditional suspension. The rack and pinion type occupies less lateral space, and the energy recovery power is increased by 40% after the installation of mechanical motion rectifier, with an average recovery power of 15.4 W, and the high-speed driving noise is 10~15 dB higher than that of the ball screw type. The average feedback power of the Audi eROT single motor is 100~150 W, and the maximum power on rough roads is 613 W, which can reduce CO_2 emissions by 3 g/km.

The linear electromagnetic suspension has the fastest response speed, with a cylindrical linear motor response time of only 3~5 ms and a power density of up to 2.5 kW/kg, but there is an end effect, the magnetic field is nonlinear, and the damping force fluctuation needs to be compensated by algorithm.

4.2 Performance Optimization Results

The use of three-coil symmetrical arrangement + quasi-Halbach array can reduce the main power attenuation rate of the actuator to 4.18%, and the thrust density is significantly improved. Linear switched reluctance motors (LSRAs) have peak forces of up to 2000 N and continuous forces of 500 N, which are resistant to high temperatures and have lower costs, but the thrust ripple is greater than that of permanent magnet synchronous linear motors.

The transmission efficiency is better than 4 mm when the ball screw lead is 6 mm, but the damping adjustable range is reduced; The lightweight design controls the suspension resonance frequency offset induced by inertial mass to less than 3 Hz, significantly improving wheel grounding.

High-temperature resistant permanent magnet materials can increase the upper limit of motor operating temperature from 150 °C to 250 °C, reducing the risk of high-temperature demagnetization. The high-temperature resistant insulation material can increase the allowable temperature rise of the winding from 120 K to 180 K, and enhance the adaptability to extreme working conditions. Under continuous bumpy conditions, the temperature rise of the motor will directly affect the electromagnetic performance and component life, and thermal management is the key to long-term stable operation.

4.3 Discussion

Rotary and linear electromagnetic suspension present a typical trade-off between performance, cost and space: the ball screw type has the highest comprehensive cost performance and is suitable for mass production and popularization; the linear response and efficiency are the best, but the control complexity and cost are higher. The rocker arm type is adapted to the high-end intelligent chassis, but the structure and calibration are difficult; nonlinear damping and inertia quality are the key factors affecting comfort, and the matching of opening speed and damping deficiency area directly determines the vibration isolation effect; the energy feedback is significantly affected by road conditions, vehicle speed, and transmission mechanisms, and mechanical rectifiers, one-way clutches, hydraulic rectifier bridges, and other mechanisms can effectively improve the recovery efficiency, but will increase mechanical loss and noise.

5. Conclusion

(1) Electromagnetic suspension has formed two major technical routes: rotary type and linear type, ball screw type is the first choice for industrialization at this stage, linear type represents the direction of high performance, and rocker type fits the trend of intelligent chassis integration.

(2) The electromagnetic suspension has millisecond response, wide damping adjustment, and 30%~60% energy conversion efficiency, which can significantly improve smoothness and stability, while recovering vibration energy to meet the low-carbon and intelligent needs of new energy vehicles.

(3) Performance optimization needs to be promoted from the perspective of electromagnetic topology, mechanical lightweight, and thermal management, and the optimization of mechanical characteristics is the most cost-effective, and nonlinear damping matching and inertial mass suppression are the core to improve the actual vehicle effect.

(4) Structural integration and lightweighting: promote the integrated design of "suspension-motor-controller", use compact topology and lightweight materials to control the increment of non-sprung load mass within 5 kg, and solve the problem of chassis space constraint.

(5) Adaptability to extreme working conditions: develop high-temperature anti-demagnetization magnets, low-temperature high-power drive circuits, and active thermal management systems to improve reliability and efficiency in continuous bumps, high and low temperature environments.

(6) Low-cost and high-reliability design: simplifying motor topology, integrating transmission mechanisms, extending the life of rotating components, improving the air gap accuracy of linear motors and electromagnetic compatibility with ECUs, and accelerating large-scale applications.

(7) Intelligent network integration: combine road surface recognition and vehicle-road collaboration to realize suspension prediction and control, expand intelligent functions such as motion sickness prevention, active obstacle crossing, and welcome posture, and support high-end intelligent driving.

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