Research and Development Review of In-Wheel Motor Drive Technology for New Energy Vehicles

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Abstract

With the rapid development of new energy vehicles, in-wheel motor drive control technology has become the ultimate form of future distributed drive control technology development. The in-wheel motor of electric vehicles directly integrates the drive motor inside the wheel hub to drive the wheels, featuring flexible control, higher power transmission efficiency, and space-saving advantages. This paper introduces the technical concepts related to in-wheel motors, analyzes the current status of domestic and international technology development and application, summarizes the current development bottlenecks and countermeasures of in-wheel motors, and finally looks forward to the future development direction of in-wheel motors, providing a reference for the technological development of in-wheel motors for new energy vehicles.

Keywords

New energy vehicles;In-wheel motors; Distributed drive; Application strategies.

1. Introduction

Driven by the dual background of global energy transition and environmental governance, new energy vehicles play an increasingly important role in the automobile consumer market. With their advantages of high cost-effectiveness and high comfort, they have gradually become a preferred means of transportation for consumers. According to the statistical data from the China Association of Automobile Manufacturers, in 2024, the sales volume of new energy vehicles in China reached 12.866 million units, a year-on-year increase of 35.5%, accounting for 40.9% of the entire automobile consumer market. In the first half of 2025, the sales volume of new energy vehicles in China reached 15.653 million units, with major brands including BYD, SAIC, Changan, and Geely [1]. It is evident that the development of new energy vehicles has become a major trend in the automobile industry, and their position in the automobile market is increasingly prominent.

As the "brain" of the power system of new energy vehicles, the motor drive controller plays a crucial role in improving the driving and operational performance of vehicles. Currently, the common drive control forms of new energy vehicles mainly include centralized control and distributed control. Centralized drive control refers to a method where a central controller uniformly controls the various drive systems of the vehicle; distributed drive control disperses the driving power to multiple independent motors (such as wheel-side motors and in-wheel motors) and achieves control through the collaboration of multiple controllers. As one of the representative implementation forms of distributed drive control, in-wheel motors highly integrate the drive motor, transmission mechanism, and even the braking system into the wheel hub space, realizing direct control of the wheels and improving transmission efficiency and vehicle flexibility. With its compact structure, in-wheel motor control increases the available space inside the vehicle to a certain extent and greatly reduces the overall vehicle weight; with its advantages of high maneuverability and comfort, it has attracted the attention of some domestic and foreign automobile manufacturers, who have initiated the research and development of related technologies.

2. Concept of In-Wheel Motor Drive Technology

2.1. Concept and Structure of In-Wheel Motors

An in-wheel motor is a drive control method that highly integrates the power system, transmission device, and braking system inside the wheel hub, representing a new mode of motor drive. This drive system can shorten the drive transmission path from the motor to the wheels, significantly improving transmission efficiency and enabling more flexible control of wheel parameters such as torque and speed. The in-wheel motor consists of a motor body, inverter, controller, braking system, sensor, heat dissipation system, bearing, and other components, and its structure is shown in Figure 1. Compared with traditional motors, the in-wheel motor eliminates external transmission systems (including couplings/pulleys, differentials, etc.), simplifying the motor structure to a certain extent.

Fig. 1 Structure of In-Wheel Motor

2.2. Classification of In-Wheel Motors

In-wheel motors can be divided into direct-drive type and reduced-speed drive type based on the presence of a reduction mechanism, and into permanent magnet synchronous in-wheel motors, asynchronous induction in-wheel motors, switched reluctance in-wheel motors, and brushless DC in-wheel motors based on the motor type.

The structural principle of the direct-drive in-wheel motor is that the motor rotor is directly rigidly connected to the wheel hub, eliminating intermediate transmission components. It generally adopts a low-speed external rotor permanent magnet synchronous motor. Since the external rotor of the direct-drive motor is directly integrated with the wheel hub through a high-strength mechanical coupling structure, the rotational speed of the wheel is the same as that of the motor[2], with the speed controlled at approximately 1500 rpm. Taking the Protean Pd18 as an example, its maximum speed is 1600 rpm, and it uses DIN 912 standard 12.9-grade bolts (8×M16) to rigidly connect the rotor housing to the rim flange, matched with an HSK80-type positioning spigot (coaxiality ≤ 0.03 mm)[3].

The reduced-speed drive in-wheel motor integrates a reduction mechanism (usually a planetary gear or parallel shaft gear) between the wheel and the motor. Its working principle is that the high-speed external rotor motor outputs high-speed and low-torque power, which is then converted into low-speed and high-torque power through the reduction mechanism to finally drive the wheel rotation. The addition of the reduction mechanism enables the conversion between the high-speed and low-torque of the motor and the low-speed and high-torque of the wheel, thereby expanding the range of motor options. A comparison between the two types of motors is shown in Table 1.

Table 1. Comparison between Direct-Drive and Reduced-Speed Drive In-Wheel Motors

Drive Form	Direct-Drive Type	Reduced-Speed Drive Type
Structural Form	External rotor	Internal rotor
Rotational Speed	Low (approximately 1590 rpm)	High (up to 6000 rpm or more)
Reduction Mechanism	None	Available
Advantages	No gear transmission loss, higher energy conversion efficiency; Direct motor drive, flexible control and fast response; No reduction mechanism, space-saving	Increased torque through the reduction mechanism, realizing high torque output; Miniaturized motor, saving interior space and reducing vehicle weight; Low cost
Disadvantages	Relies on motor torque, requiring large-weight and large-volume motors; High motor cost; Limited low-speed performance	Mechanical loss in reduction gears, low efficiency; High noise; Increased unsprung mass
Application Cases	Passenger cars, high-performance vehicles, special vehicles	Commercial vehicles, mining trucks, logistics vehicles

3. Development History of In-Wheel Motor Drive Technology

3.1. Early Technology Origin

As early as 1896, Ferdinand Porsche, the founder of the German brand Porsche at the age of 21, made innovations in the generator of electric vehicles and obtained a British patent for in-wheel motors [4]. In 1898, Porsche designed the Egger-Lohner C.2 Phaeton, a pioneering vehicle model. This car was driven by an octagonal electric motor, and the first prototypes were equipped with two motors on the front wheel hubs, similar to modern two-wheeled electric vehicles, as shown in Figure 2. On April 14, 1900, an electric vehicle named Lohner-Porsche developed by Porsche made its debut at the Paris World Expo. Gasoline Porsche equipped each wheel with an in-wheel motor, creating the world's first four-wheel drive electric vehicle [5], This electric vehicle adopted a series hybrid power system, where two gasoline engines drove generators to charge the battery, greatly improving the cruising range [6].

Fig. 2 Egger - Lohner C.2 Phaeton.

3.2. Technology Dormancy Period

Around the 1920s, due to the obvious advantages of internal combustion engine vehicles in cruising range and refueling convenience, coupled with sufficient supply and low price of oil resources, the development of electric vehicles entered a technology dormancy period. In 1942, Porsche attempted to apply in-wheel motor technology to the VK.45.01(P) heavy tank, but due to the complex control system and insufficient reliability, it failed to be widely applied in the end [7].

3.3. Technology Revival and Modern Application

In the 1990s, with the enhancement of environmental protection awareness and the emergence of the oil crisis, in-wheel motor technology regained attention. In 1991, Toyota Motor Corporation of Japan attempted to use in-wheel motor drive in its concept car EV-30. In 2003, Mitsubishi Corporation adopted in-wheel motor technology in its Colt EV concept car, achieving a power output of 25 kW per motor [8]. After 2010, in-wheel motors entered a period of rapid development. In 2011, Protean Electric of the UK developed the Pd18 in-wheel motor, with a single-motor power of 75 kW and a torque of 1000 N·m[9]. In 2013, NSK Corporation of Japan developed a wheel hub module integrating braking, suspension, and drive functions [10].

In-wheel motor technology has a history of nearly a century since its birth, but unfortunately, it has been rarely applied in new energy vehicle models. Japanese manufacturers started the research and development of in-wheel motor technology earlier and are in a leading position, while domestic manufacturers are also gradually promoting the research and development of in-wheel motor technology.

4. Domestic and International Research Status of In-Wheel Motor Drive Technology

Many foreign companies and manufacturers have conducted special research on in-wheel motors and have begun to apply them to actual products, which is mainly reflected in two aspects: one is the integrated electric system developed by R&D teams represented by automobile parts manufacturers, and the other is the electric vehicles jointly developed by vehicle manufacturers and in-wheel motor drive system manufacturers[11].

Although the domestic in-wheel motor drive technology module started late, it has gradually developed under the drive of national policies and the market. Some technologies have reached the international advanced level, but overall, the domestic research on in-wheel motor drive technology is not yet mature. Therefore, China needs to increase investment in the R&D of in-wheel motor drive technology to enhance international competitiveness.

4.1. International Research Status of In-Wheel Motor Drive Technology

Early foreign research on in-wheel motors mainly focused on the electromagnetic and mechanical design of the motor body and strived to break through the limits of power and torque to prove the feasibility of the technology. For example, the high-performance permanent magnet synchronous motor solution developed by Protean Electric of the UK has become an industry benchmark [12].

Currently, the core of research on in-wheel motors is to transform the in-wheel motor from an independent drive component into the intelligent core of the vehicle corner module (e-Corner), as shown in Figure 3, and study the physical integration and control integration of its steering, braking, and suspension systems. For example, companies such as NSK of Japan and Schaeffler Group of Germany integrate components and systems such as in-wheel motors, electronic braking, steering systems, and dampers into a single wheel-end module, allowing each wheel to be independently driven and steered. The purpose is to solve symbiotic problems such as heat dissipation[13].At the control level, the research focus is to realize the collaboration between driving torque and the functions of ESC (Electronic Stability Control), ABS (Anti-lock Braking System), and TCS (Traction Control System) through the vehicle domain controller. For example, using the torque difference between the two sides of the wheels to generate direct yaw moment, thereby realizing faster and more accurate vehicle dynamics control than the traditional ESC, which has become the focus of distributed drive function development [14].

Fig. 3 NSK Vehicle Corner Module.

4.2. Domestic Research Status of In-Wheel Motor Drive Technology

Domestic research on in-wheel motor drive technology shows different characteristics from foreign research, such as the evolution of technology, the focus of industrialization, and the challenges to be faced in the future. Great achievements have been made in basic theoretical research and application in specific scenarios, but there is still a certain gap between the domestic technology maturity and application in high-end passenger cars and the international top level, leaving huge development potential and space.

At the technical R&D level, research conducted by some domestic universities and industries has laid a theoretical foundation for in-wheel motor drive technology. For example, Harbin Institute of Technology, Beijing Institute of Technology, and other universities have conducted in-depth exploration in the optimization of electromagnetic design and torque control strategies of in-wheel motors, providing important theoretical support for the initial development of the industry[15]. The in-wheel motor products of Zhejiang Asia-Pacific Mechanical & Electrical Co., Ltd. have achieved mass production and successfully matched a variety of new energy commercial vehicles and special vehicles, demonstrating significant progress in domestic industrialization[16],as shown in Figure 4.

Fig. 4 Zhejiang Asia-Pacific In-Wheel Motor M700.

In terms of technology maturity, domestic electromagnetic and mechanical design of the motor body is relatively mature, and the real challenges focus on the system engineering level, such as heat dissipation capacity—a key issue restricting the power output of in-wheel motors. Although domestic manufacturers generally adopt liquid cooling or oil cooling solutions, there is still a gap between their process level and material foundation and the international top level in terms of cooling efficiency and lightweight [17].

5. Application Overview of In-Wheel Motor Drive Technology

5.1. Application in the Passenger Car Field

In the passenger car field, the application of in-wheel motors is currently mainly in concept cars and small-batch mass-produced cars, and large-scale commercial promotion has not yet been realized. Nevertheless, with its unique drive method and structural advantages, in-wheel motor drive technology has shown broad application prospects in multiple market segments, especially in improving vehicle power, maneuverability, and flexibility.

5.1.1. High-Performance Vehicles

The ProteanDrive product developed by Protean Electric, a British technology company, is a representative in this field. This product adopts an external rotor permanent magnet synchronous motor design and is highly integrated into the wheel hub. Protean Electric has created demonstration vehicles for a number of international brands, such as test vehicles modified based on models including the Ford F-150 and Mercedes-Benz E-Class. These vehicles generate a yaw moment for auxiliary steering by applying different torques to the inner and outer wheels during cornering, greatly improving the agility of the vehicle [12].

5.1.2. New Architecture Vehicles

Aptera Motors, an American new energy vehicle company, has adopted the high-performance in-wheel motor L1500 from Elaphe Propulsion Technologies of Slovenia in its launched solar electric vehicle. The peak power of a single motor exceeds 110 kW, and the torque is as high as 1700 N·m, enabling the Aptera three-wheeled model to achieve 100 km acceleration performance and ultra-low energy consumption, as shown in Figure 5. This practice provides a new model for future lightweight and efficient means of transportation[18].

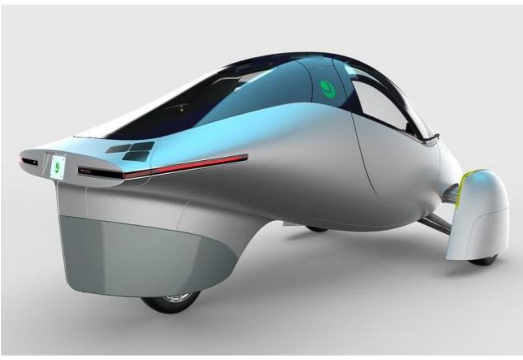

Fig. 5 Aptera Three-Wheeled Solar Electric Vehicle.

5.2. Application in the Commercial Vehicle Field

The commercial vehicle field is the first field where in-wheel motors have realized large-scale commercial application. Some models of the unmanned electric container trucks developed by China National Heavy Duty Truck Group adopt in-wheel motor drive technology, realizing special modes such as "crab walking" and in-situ steering, which greatly improves the operation efficiency and flexibility in narrow working spaces and reduces operating costs[19].

The independently developed in-wheel motor drive system of Zhejiang Asia-Pacific Mechanical & Electrical Co., Ltd. has been mass-applied to low-floor bus fleets in many domestic cities, such as new energy buses in Hangzhou and Shenzhen. It completely eliminates the traditional central differential and drive shaft, realizing a fully flat carriage floor, reducing the overall vehicle center of gravity, and enhancing driving stability[20].

5.3. Application in Special Vehicles

General Motors of the United States has collaborated with the Department of Defense to develop the Surus (Silent Utility Rover Superstructure) concept platform, which adopts a skateboard chassis driven by hydrogen fuel cells and in-wheel motors, demonstrating its application prospects in military logistics and special mission vehicles [21], as shown in Figure6.

Fig. 6 SURUS Hydrogen Fuel Cell Vehicle Platform.

6. Development Bottlenecks and Solutions of In-Wheel Motor Drive Technology

6.1. Heat Dissipation Issue

In-wheel motors face dual heat dissipation challenges from space constraints and road thermal shocks. Due to electromagnetic loss, iron loss, and mechanical loss, a large amount of heat is generated between components such as the stator, rotor, and bearing. If the heat is not dissipated in a timely manner, it will seriously affect the service life of the in-wheel motor and even vehicle safety. The heat dissipation process of in-wheel motors mainly includes three methods: heat conduction (heat transfer through lattice vibration or free electron migration inside solid or fluid media), heat convection (heat transfer through intermolecular interaction between fluid and solid surfaces), and heat radiation (heat transfer in the form of electromagnetic waves). Among them, the proportion of heat transfer by heat radiation is relatively small and can be ignored[22]. Currently, the mainstream thermal management technologies for in-wheel motors include liquid cooling, self-cooling, and oil cooling. Zhou Ning from Hubei University of Arts and Science comprehensively analyzed the heat transfer mechanism of in-wheel motors, conducted specific research on the cooling system of in-wheel motors, and innovatively applied the Tesla valve flow channel, finally designing the optimal comprehensive performance solution: 1% CuO nanofluid + optimized Tesla valve flow channel. The overall maximum temperature of the motor was reduced by 21.3% compared with the traditional water-cooled spiral flow channel (from 145.5°C to 114.5°C) [23].

Wang Hailong from PetroChina Daqing Petrochemical Company calculated the temperature field through software and conducted temperature rise simulation analysis on the 196-kW permanent magnet synchronous in-wheel motor under different oil immersion conditions.

Finally, it was concluded that the simulation effect was optimal when the oil immersion parameter was 1/3, and the motor cooling effect was the best [24].Figures 7 and 8 show the relationship between oil immersion conditions and oil wear loss, and the overall temperature distribution of the motor, respectively. It can be seen that the higher the oil level, the smaller the oil wear loss, and the worse the motor cooling effect. Therefore, it is necessary to find a suitable oil immersion level.

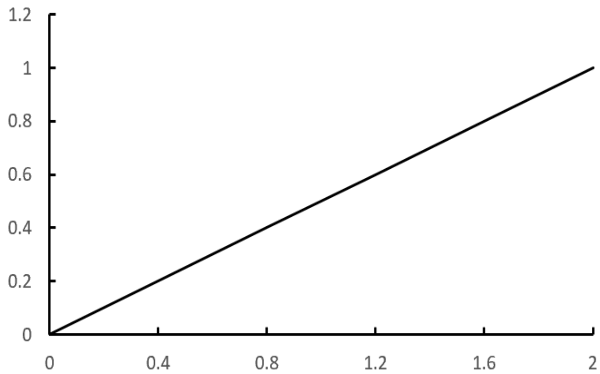

Fig. 7 Relationship between Oil Immersion Coefficient and Oil Wear Loss.

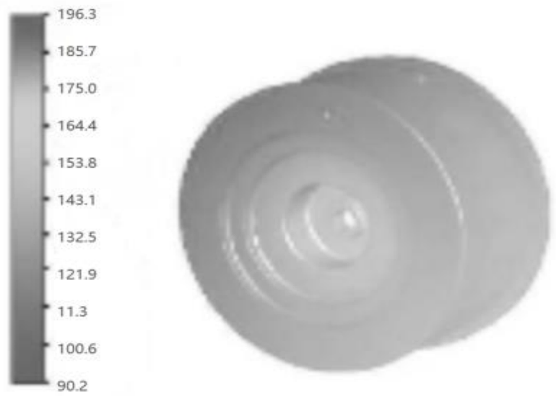

Fig. 8 Overall Temperature Distribution.

6.2. Increase in Unsprung Mass

The highly integrated structure that concentrates components such as the motor, reducer, and brake at the wheel end makes the increase in unsprung mass an inevitable drawback of in-wheel motors. The larger the unsprung mass, the worse the ability of the wheels to track road unevenness, and the lower the ability to maintain tire ground contact, which causes the vehicle body to receive more vibrations and reduces riding comfort[17]. At the same time, excessive unsprung mass will generate huge inertial forces during vehicle steering and braking, affecting the response speed of the suspension. In extreme cases, the difficulty of vehicle stability control increases[25], and it will also increase the friction between the wheels and the ground, greatly reducing the service life of the wheels and affecting driving safety.

To solve such problems, high-strength, lightweight materials with good thermal conductivity (such as aluminum alloys and magnesium alloys) can be used to manufacture motor housings and suspension components, and carbon fiber composite materials can be applied to rotating components such as the motor rotor. This can significantly reduce the moment of inertia while ensuring strength, which is one of the most effective ways to reduce weight [26]. In addition, active or semi-active suspension systems (such as CDC continuously variable damping suspension) can be adopted to suppress the vibration of unsprung mass by adjusting the damping force in real time.

6.3. System Sealing Performance and Adaptability to Harsh Environments

Since in-wheel motors are highly integrated into the wheel hub, they inevitably have to deal with the erosion of corrosive media such as water and mud for a long time, so the durability requirements for seals are extremely high. At the same time, severe high-frequency impacts and vibrations from the road will seriously affect the service life of internal components such as bearings, gears, and electronic components of the motor, and may cause problems such as bearing electric corrosion and sensor failure [27].

To solve the problems of sealing performance and adaptability of in-wheel motors, solutions such as multi-channel sealing, high-performance lip seal rings, and nitrogen filling can be adopted, and the housing can use corrosion-resistant coatings or materials. At the same time, special anti-electric corrosion treatment is performed on the bearings, high-strength gear materials and processes are used, and potting treatment is performed on the PCB board and connectors to enhance their vibration resistance. Sensors are integrated into the motor to detect the health status of the motor through big data and AI algorithms and perform maintenance in a timely manner.

6.4. Permanent Magnet Demagnetization Issue

For in-wheel motors widely using permanent magnets, irreversible demagnetization of permanent magnets is a decisive factor related to their reliability and service life, and the operation of in-wheel motors in harsh environments increases the risk of permanent magnet demagnetization. The magnetic properties of neodymium-iron-boron permanent magnets are extremely sensitive to temperature. When the in-wheel motor is overloaded or operates at high power continuously, the internal temperature rise can be too high. Once the demagnetization critical temperature is exceeded, irreversible demagnetization will occur, leading to a serious decline in motor performance [28]. Under the action of high peak current, a strong counter-magnetic field will exert a strong demagnetizing effect on the permanent magnets.

In response to the above problems, there are multiple countermeasures and solutions. For example, high-coercive-force permanent magnets with heavy rare earth diffusion combined with lightweight materials such as carbon fiber can be used. Such magnets have significantly enhanced anti-demagnetization ability at high temperatures, which can effectively cope with demagnetization risks and contribute to lightweight design [28].

7. Prospect of In-Wheel Motor Drive Technology

Although in-wheel motors face extremely difficult problems and challenges in practical applications, such as motor overheating leading to demagnetization and increased unsprung mass, it is undeniable that in-wheel motor drive technology has great exploration space and is likely to become one of the mainstream drive methods in the future. Its future development direction will be mainly reflected in key dimensions such as lightweight, intelligentization, miniaturization, and convenience.

7.1. Lightweight

Achieving lightweight is the key to solving the problem of increased unsprung mass of in-wheel motors. In the future, carbon fiber composite materials will not only be used for housing but also for the motor rotor, which can significantly reduce the moment of inertia while ensuring extremely high strength. In addition, high-strength aluminum alloys, magnesium alloys, and composite materials will be combined with advanced design methods such as topology optimization to achieve comprehensive weight reduction from components to systems [26].

7.2. Intelligentization

Based on four-wheel independent steering and drive, vehicles equipped with in-wheel motors can realize special modes such as "crab walking" and "in-situ steering". This can not only greatly improve flexibility in narrow spaces but also is expected to give birth to new vehicle forms and traffic rules in the future, such as providing unprecedented layout flexibility for shared autonomous buses (Robotaxis) in smart cities[15]. Moreover, by integrating sensors and advanced AI algorithms, in-wheel motors can real-time sense key state parameters such as tire force and provide environmental information for the vehicle's overall control system in a timely manner. On this basis, the torque vector distribution function based on algorithms such as model predictive control will enable the vehicle to achieve more stable body control than the traditional ESC system, providing safety guarantees for autonomous driving [14].

7.3. Convenience

Future in-wheel motor systems will tend to adopt unified standard modular interface designs, covering both electrical connections and mechanical fixing. Through quick-plug electrical connectors and flange-type mechanical docking structures, the disassembly and assembly process of the entire drive assembly can be as efficient and convenient as changing tires in a racing car, which can greatly improve the after-sales maintenance efficiency [29].

8. Summary

In-wheel motor drive technology has unlimited development potential and space in the new energy vehicle industry and has become the ultimate form of future distributed drive control. With increasing international attention to environmental issues and the strengthening of energy protection efforts, traditional automobiles will be difficult to meet social needs, and electric vehicles using in-wheel motors as the drive technology will have broader application prospects. In-wheel motors have strong flexibility in controlling vehicle steering and torque, which can further improve vehicle driving performance and energy utilization efficiency, and show great advantages in space structure utilization and dynamic control. At the same time, there are also rigid problems such as difficult heat dissipation management and increased unsprung mass, but it is believed that these problems can be solved with the development of technology in the future.

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