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Research Progress on Magnetic Wheel Transmission with Magnetic Coupling Speed Regulation

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Abstract

Fluid electromechanical equipment, such as fans and water pumps, accounts for a large proportion of total energy consumption in China. Throttle speed regulation results in substantial energy loss, while variable-frequency speed regulation is prone to electromagnetic interference and thus limited in application scenarios. A magnetic wheel transmission based on magnetic coupling transfers power via non-contact magnetic fields, featuring soft start, vibration reduction, energy savings, and overload protection. This paper summarizes the structures and speed regulation mechanisms of various magnetic couplers, including cylindrical, disc, and conical types. It systematically analyzes the performance characteristics of permanent magnet materials, magnetic conductive materials, insulating materials, and supporting structural materials for magnetic wheel transmission. It compares the loss characteristics and adaptability to working conditions of electrical steel, soft magnetic composites, and cobalt-based alloys. The significance of insulation coating for suppressing eddy-current losses in soft magnetic composites is clarified. Moreover, the research progress in structural optimization, electromagnetic simulation models, and eddy-current heat-dissipation design for magnetic couplers is reviewed. Engineering cases show that when this transmission device is applied to equipment in thermal power, municipal engineering, petrochemical, coal mining, and other industries, the power-saving rate ranges from 11% to 34.62%, and it can effectively reduce vibration and operational & maintenance pressure. At present, existing research still has deficiencies, such as insufficient comparison of multiple speed-regulation schemes and room for improvement in high-frequency losses and torque density. Finally, the future research directions, including high-temperature superconducting magnetic materials, novel electromagnetic calculation algorithms, and adaptive magnetic circuit regulation systems, are prospected. This study provides theoretical support for the energy-saving transformation of fluid load equipment and for the engineering application of magnetic transmission equipment.

Keywords

magnetic coupling, magnetic wheel transmission, permanent magnet materials, structural optimization, energy-saving transformation

1. Introduction

According to calculations by the Ministry of Industry and Information Technology of China, 21 categories of electromechanical products, including motors, transformers, fans, and water pumps, account for approximately 70% of total national electricity consumption. Among them, the installed capacity of motors exceeds 3 billion kilowatts, accounting for more than 50% of total social electricity consumption and mainly driving fluid loads such as fans, pumps, and compressors [1-2]. Such fluid equipment operates under complex, variable working conditions, requiring frequent adjustment of parameters such as flow rate, pressure, and head. At present, throttling and variable-speed regulation are the two main regulatory methods used in industry. Throttling regulation features simple operation and structure, yet it has many drawbacks, such as significant energy loss, low regulation accuracy, severe equipment wear, strong operating vibration, slow response, and easy medium leakage [3]. Centered on variable-frequency speed regulation, variable-speed regulation has been widely applied due to its high efficiency, high precision, and high degree of automation, effectively solving the energy consumption problems of throttling regulation [4-5]. Nevertheless, this technology has inherent defects: it easily causes harmonic pollution and electromagnetic interference during operation, has limited dynamic response capability and high operation & maintenance costs, restricting its application in special industrial scenarios with explosion-proof requirements and strong interference.

As a novel non-contact power transmission and regulation technology, magnetic coupling speed regulation stands out for its frictionless operation, stable operation, and strong adaptability. It provides soft-start for motors, overload protection, and stepless, energy-saving speed regulation, offering significant advantages in industrial applications [6]. The core magnetic wheel transmission structure balances high transmission efficiency and a wide speed regulation range, addressing many pain points of traditional speed regulation technologies. Current academic research on speed regulation technologies for fluid equipment mostly focuses on optimizing variable-frequency speed regulation or on single-performance analyses of magnetic couplings. There is a lack of systematic comparisons among various speed regulation technologies, and in-depth studies on adaptability to working conditions, energy-saving mechanisms, and operational stability of magnetic wheel transmissions are insufficient, hindering their large-scale application in complex industrial scenarios.

This study compares the comprehensive performance of traditional speed regulation and magnetic-coupling speed regulation, analyzes the working mechanism of magnetic wheel transmission, explores the influence rules of key parameters on equipment operational performance, optimizes the structural design, and verifies its engineering application advantages. It aims to provide theoretical support for energy-saving transformation and the safe operation of fluid equipment, such as fans and water pumps, and to offer references for the green, low-carbon, safe, and efficient development of industrial electromechanical equipment.

2. Classification, Structure, and Working Principle of Magnetic Speed Regulators

2.1 Classification of Magnetic Couplers

Magnetic couplers can be classified in various ways. Based on magnetic circuit structure, magnets are divided into radial, axial, and hybrid types. In terms of motion form, they include rotation-rotation, linear-linear, and rotation-linear types [7]. Based on different magnetic coupling regulation modes, they are categorized into disc type, cylindrical type, concentric shaft type, conical type, slotted type, and hybrid type.

2.2 Structure and Working Principle of Magnetic Couplers

Magnetic couplers operate by exploiting magnetic forces and transmit power through magnetic fields [8]. Their core components are magnets and conductor discs. Generally, the magnets are connected to the driving motor shaft, while the conductor rotors are linked to the working machine shaft. An air gap exists between the magnets and conductors. By adjusting the air gap or coupling area between them, the magnetic flux, eddy currents, and torque can be controlled to achieve transmission and speed regulation [9]. The structures and working principles of typical magnetic couplers are as follows:

The cylindrical magnetic coupling device comprises a driving rotor, an air-gap layer, and a driven rotor. The driving rotor is connected to the motor, and the driven rotor, equipped with radially magnetized permanent magnets, is connected to the load. The rotation of the driving rotor generates an induced magnetic field via eddy current, which interacts with the magnetic field of permanent magnets to drive the equipment. Speed regulation is realized by adjusting the coupling area [2].

The disc-type magnetic coupling device comprises a conductor disc and a permanent magnet disc. The motor shaft is connected to a copper conductor disc, and the load shaft is fitted with an axially magnetized permanent magnet-driven disc. The motor drives the conductor disc to cut magnetic field lines, generating an eddy current and an induced magnetic field. Torque is transmitted through the interaction between the induced magnetic field and the permanent magnets' magnetic fields. Torque and rotational speed are regulated by varying the distance between magnets and conductors to adjust the magnetic flux [2].

The concentric shaft magnetic coupling device is made up of a permanent magnet rotor, a conductor rotor, and an air gap, and its working principle is basically the same as that of the cylindrical type [10].

The conical magnetic coupling device comprises a permanent magnet rotor, a conductor rotor, and an air gap. The magnetic field of permanent magnets cuts the conductor rotor, generating an induced current and an induced magnetic field, and the rotors rotate due to magnetic field coupling. Speed regulation is achieved by adjusting the axial coupling length of the two rotors to change the magnetic flux [11].

The slotted magnetic coupling device includes a conductor rotor and a permanent magnet rotor. The permanent magnets are axially magnetized and arranged alternately around the circumference. The rotational speed difference during rotor operation generates an eddy current and an induced magnetic field within the conductor. Torque is transmitted via magnetic field coupling, and torque and rotational speed are regulated by adjusting the air gap thickness between the rotors [12].

The hybrid magnetic coupling device comprises inner and outer rotors, each equipped with carriers, magnetic steel, and fasteners. The north and south poles of the inner and outer magnetic steels are arranged alternately with an air gap reserved in between. The motor drives the outer rotor to rotate, and torque and rotational speed are transmitted via magnetic coupling in the air gap. Flexible regulation of speed and torque is achieved by adjusting the air-gap range [13].

3. Materials for Magnetic Wheel Transmission Components

3.1 Permanent Magnet Materials

As the core materials for converting electric energy to mechanical energy, permanent magnet materials directly affect the efficiency, torque transmission capacity, and operating temperature range of couplers. At present, rare-earth permanent magnets are widely used in industrial applications. Among them, permanent ferrite magnets feature abundant raw materials, good corrosion resistance, excellent temperature stability, and high resistivity, but their magnetic capacity is relatively low [14]. Samarium-cobalt (Sm-Co) and neodymium-iron-boron (Nd-Fe-B) rare earth alloys deliver superior magnetic performance [15]. Sm-Co materials possess excellent magnetic properties, good corrosion resistance, high-temperature resistance, and strong oxidation resistance. However, structural defects in iron-containing magnets limit performance improvement. High-iron Sm-Co permanent magnets have become a research hotspot [16]. Nd-Fe-B magnets exhibit ultra-strong magnetic properties, yet their low Curie temperature and poor thermal stability limit their use in high-temperature environments. Developing sintered Nd-Fe-B magnets with high coercivity is the key to improving product performance [17].

To address the low torque density of traditional permanent magnet materials, which cannot meet the demands of high-power transmission, high-temperature superconducting magnetic materials can significantly enhance magnetic power transmission performance, thanks to their high current-carrying capacity, strong trapped magnetic fields, and Meissner effect [18]. As a rare-earth-free material, alnico permanent magnets have high remanence and outstanding temperature stability, making them a popular research subject. Nevertheless, their low coercivity leads to low magnetic energy product and restricts their application [19].

Research on permanent magnet technology began relatively late but has developed rapidly in recent years. The magnetic energy product of traditional permanent magnet materials, such as ferrite magnets, is only 40-60 kJ/m^3. In contrast, the theoretical magnetic energy product of novel permanent magnet materials represented by Nd-Fe-B reaches 320~360 kJ/m^3, with the output power up to 300 kJ/m^3. Although the theoretical magnetic energy product of SmFeN-based permanent magnets is less than 240 kJ/m^3, they exhibit good ductility and are amenable to processing [20].

3.2 Magnetic Conductive Materials

Magnetic conductive materials form the magnetic circuit of magnetic couplers, and their performance directly affects magnetic field transmission efficiency and power loss. Li G et al. [21] systematically evaluated the performance of three types of magnetic conductive materials, including electrical steel, soft magnetic composites, and cobalt-based soft magnetic alloys. They explored the relationships between various material parameters and the output characteristics of magnetic transmission systems. The results show that soft magnetic composites can effectively reduce core loss, with this advantage becoming more pronounced at higher frequencies.

The three types of magnetic conductive materials have distinct characteristics. Electrical steel is low-cost and performs well at low frequencies, but it is only suitable for two-dimensional low-speed magnetic gears with prominent high-frequency losses. Soft magnetic composites can be fabricated into three-dimensional magnetic structures and offer significant advantages in reducing high-frequency losses, but their saturation magnetic flux density is relatively low. Cobalt-based alloys have the highest saturation magnetic flux density and a high torque density. Yet, they are costly and perform poorly at high frequencies, so they are only applicable to specialized low-frequency, high-power magnetic transmission applications.

3.3 Insulating Materials

Insulating media are filled inside soft magnetic composites to form insulating barrier layers between magnetic powder particles, blocking eddy current paths inside and among particles and effectively suppressing eddy current loss. It is generally acknowledged that constructing high-performance coated insulation structures with high density, strong interfacial adhesion, and good insulation properties is key to overcoming the bottleneck of high-frequency loss in soft magnetic composites. Based on sorting out the key technologies of insulation coating and powder gradation for soft magnetic composites, He Jiayi et al. [22] noted that the controllable preparation of high-performance inorganic insulation coating layers is currently a research hotspot in the field of soft magnetic composites.

3.4 Other Structural Materials

There are multiple methods for fixing permanent magnets to rotors, including bonding, mechanical fastening, composite materials, and high-strength sheaths. Bonding or mechanical fixing (bolts or rivets) can be adopted for low-speed applications, while composite materials or high-strength sheaths are recommended for high-speed applications. The combination of bonding and mechanical fixing is suitable for scenarios requiring high precision. For high-speed rotors, it is recommended to fix the materials directly to the rotor surface, and sheaths shall be installed on the permanent magnet surfaces to ensure safe operation. There are non-magnetic alloy sheaths and composite sheaths, among which carbon fiber composite sheaths have excellent stiffness, strength, and temperature resistance [23]. Injection molding and glue pouring processes are mainly applicable to cases with large gaps between magnetic steels and iron cores [24]. In contrast, EP-type epoxy structural adhesives can be used to fix magnetic steels with small gaps [25]. Appropriate materials shall be selected for the structural components of the magnetic wheel transmission, such as shells, shafts, and bearings, to ensure mechanical strength, wear resistance, and corrosion resistance.

The selection of materials for magnetic wheel transmission components is critical to ensuring the performance, efficiency, and reliability of equipment, covering permanent magnet materials, magnetic conductive materials, insulating materials, and other structural materials. When selecting materials for magnetic coupling devices, factors such as cost, processing technology, environmental adaptability, and service life shall be comprehensively considered to ensure efficient, reliable, and stable operation in practical applications.

4. Structural Design and Optimization

4.1 Structural Form Optimization

The initial model of magnetic couplers was proposed by Nehl T et al. [26], which realized speed regulation by adjusting the air gap between magnets and conductors. To expand the speed regulation range of magnetic couplers and improve the utilization rate of permanent magnet materials, Zhang Xiaofeng et al. [27] took the cylindrical solid magnetic coupler with intermittently arranged permanent magnets as the research object. They obtained the optimal structural parameters: a pole arc coefficient of 0.8, a pole pair number of 6, a copper ring thickness of 4 mm, and a copper ring length-to-thickness ratio of 1. Liu Baoxiang et al. [28] proposed a combined speed regulation method integrating variable-area and variable air-gap control and verified its feasibility, providing new ideas for magnetic-coupling speed regulation.

Aiming at the defects of long axial moving distance and slow displacement speed regulation of cylindrical and disc-type magnetic couplers, Ge Yanjun et al. [29] designed a conical rotor magnetic wheel coupler and verified its excellent speed regulation performance when applied to centrifugal loads. Zhu Li [30] developed a solid disc-type magnetic coupler with rotatable magnets, which adjusts output torque by changing the rotation angle of permanent magnets. Based on the layer theory model, Hang Tian et al. [31] developed the two-dimensional scalar magnetic potential method and established calculation models for the air-gap magnetic field, current density, and output torque. The accuracy of the calculation models for the air-gap magnetic field and output torque was verified through finite-element simulations and experiments.

4.2 Algorithms and Models

The traditional three-dimensional finite element method requires a heavy workload and long computation time to calculate the leakage flux coefficient. Against this background, Wang Shuang [32] proposed a three-dimensional, permanent-magnet-temperature-field-coupled finite-element analysis method, which improved the simulation accuracy of composite magnetic couplers. Combining the equivalent magnetic circuit method with the Carter coefficient and accounting for three-dimensional end effects, Yang Chaojun et al. [12] derived the electromagnetic torque formula for SAAMC. They established a speed regulation calculation model, providing theoretical references for intelligent speed regulation and the practical application of magnetic couplers. Based on the three-dimensional finite element analysis model and analytical model of disc-type permanent magnet magnetic couplers, Zhang Xiaoliang [33] analyzed the variation rule of output torque with output rotating speed, and discussed the influences of air gap length and conductor disc thickness on the characteristics of permanent magnet magnetic couplers, offering guidance for further analysis of electromagnetic characteristics of disc-type magnetic wheel couplers.

Remarkable progress has been made in optimizing performance and researching magnetic couplers. The research has evolved from the early layer theory model and initial idea of field-circuit combination to the in-depth application of finite element simulation and field-circuit coupling. Advanced three-dimensional magnetic field simulation, experimental verification & optimization results are gradually playing a positive role in innovating magnetic circuit models and torque calculation, thereby improving the control accuracy and predictive performance of magnetic transmission systems.

4.3 Eddy Current and Heat Dissipation

When conductive materials (such as copper discs) are placed in a varying magnetic field, an induced electromotive force is generated within the conductors in accordance with Faraday's law of electromagnetic induction, thereby forming closed current loops, namely eddy currents. Eddy currents generate heat, raising the temperature of the copper discs. Excessively high temperatures may cause the temperature of permanent magnets to exceed their Curie temperature, leading to demagnetization. Through electromagnetic simulation analysis of eddy current loss, Li Xiao [34] found that the eddy current distribution on the copper disc of permanent magnet magnetic couplers is uneven. Due to the skin effect, the eddy current is mainly concentrated in a thin layer on the side of the copper disc facing the permanent magnets, and the eddy current density decreases gradually from the inner surface to the outer surface along the axial direction. On this basis, a spiral groove water-cooling channel was designed with a favorable heat-dissipation effect.

In general, for high-speed magnetic couplers, a rotor layered structure and an optimized magnetic field distribution, combined with cooling systems, can be adopted to reduce eddy-current losses and heat generation. For low-speed or low-power applications, materials with high resistivity or simple cooling measures can meet the operation requirements.

The structural design and optimization of magnetic wheel transmission is a complex, multi-objective, multi-constraint process. Multiple factors, including magnetic circuit design, air gap optimization, rotor structure, shell design, torque transmission capacity, efficiency, reliability, cost, and electromagnetic compatibility, shall be comprehensively considered. Theoretical analysis, numerical simulation, and experimental verification are combined to achieve a high-performance, high-efficiency, and high-reliability design.

5. Industrial Application Status

As a non-contact transmission technology, magnetic wheel transmission transmits power through magnetic field interaction, featuring no wear, high efficiency, and low noise. It has been widely applied in municipal engineering, power plants, the petrochemical industry, coal mining, and other fields.

Table 1: Industrial Application Status

Industrial Field	Load Type	Implementation Scheme	Application Effect	Reference
Municipal Engineering	Water pump	The original direct drive of circulating water pumps was replaced by magnetic wheel speed regulation drive.	The temperature of the motor shaft decreased by 5 ℃, the power saving rate reached 11%~15%, and vibration was effectively alleviated.	[35]
Thermal Power Plant	Fan	Traditional drive of fans was transformed into magnetic wheel transmission and speed regulation mode.	The amplitude and current of the speed regulation system decreased significantly, and the energy saving rate of the motor system reached 15.01% under 75% load.	[36]
Petrochemical Industry	Cooling tower fan	The combined drive mode of motor, transmission shaft and reducer was transformed into magnetic wheel speed regulation drive.	Outstanding energy-saving effect with the maximum power saving rate of 34.62%, and the vibration of the original fan reducer was relieved.	[37]
Coal Mining	Belt conveyor	Magnetic coupling system replaced hydraulic coupling.	The transmission efficiency was increased from 76% to 93%, and the safety and reliability of coal mining transportation equipment were greatly improved.	[38]
Soda-making Industry	Main motor of calciner	Hydraulic couplers were replaced by magnetic couplers.	The starting current decreased by about 20%, the vibration of motors and reducers was reduced, and the equipment was basically maintenance-free.	[39]
Chemical Industry	Chemical centrifugal pump	Centrifugal pumps were transformed into magnetic pumps.	Energy consumption decreased by 16.9%.	[40]

The global market for magnetic transmission equipment and related services is growing year by year, and demand for high-torque magnetic transmission and speed-regulation systems is surging across traditional industries and emerging sectors. China's carbon peaking and carbon neutrality goals have brought new growth opportunities for the development of magnetic wheel transmission technology.

6. Conclusion

Magnetic coupling transmission and speed regulation technology is an innovative non-contact transmission method that transmits torque through magnetic field interaction. It has multiple advantages, including energy saving, soft start, overload protection, vibration isolation, high tolerance to coaxiality errors during installation, convenient installation & maintenance, and high reliability. Permanent magnet materials are the core materials of magnetic wheel transmission. The magnetic energy product of novel permanent magnet materials is more than twice that of traditional ones. Magnetic couplers have evolved into diverse structural forms, including disc, cylindrical, conical, toothed, and variable-area types. Three-dimensional magnetic field simulation and innovative magnetic circuit modes have achieved good application results in coupler design. Magnetic wheel transmission systems are being applied industrially in various fields and equipment, demonstrating broad application prospects and research value. Future research directions for magnetic wheel transmission systems should develop and apply high-temperature superconducting magnets and functionally graded materials to improve the magnetic energy product and heat resistance, thereby expanding the application scope. Explore new algorithms and models to optimize structural design, increase torque density, and reduce eddy-current losses. Develop adaptive magnetic-circuit regulation systems to compensate for load fluctuations dynamically.

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