

Performance Analysis of Stator Hybrid Excitation Magnetic Planetary Gear Machines

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Abstract—Drawing on the ideas of stator permanent magnet motors, hybrid planetary gears are integrated into permanent magnet motors using hybrid excitation on the stator side, and a new type of stator-hybrid magnetic planetary gear motor for steering systems is proposed. The magnetic gear motor overcomes the shortcomings of the existing magnetic gear structure and performance, and has the advantages of high reliability, strong torque transmission capacity, and large transmission ratio. At the same time, it can adjust the levitation force and power in real time as the working conditions change, improving motor efficiency. This paper focuses on the topology and working principle of the stator-excited planetary magnetic gear motor. According to the finite element analysis, the magnetic field distribution is obtained, and the rationality of the magnetic field is analyzed. Theoretical analysis and experimental results show that the magnetic circuit of the stator-hybrid excitation planetary gear motor is correct, and the torque can meet the design requirements. This method provides reference and application value for the development of high performance and low cost permanent magnet planetary gear motors.

1. INTRODUCTION

Magnetic gear has attracted great attention. In contrast to the widely used mechanical transmission systems, magnetic gears have the non-contact characteristic of transmitting torque, which has high reliability and low maintenance requirements [1]. In addition, the conventional permanent magnet synchronous motor generates torque through the interaction between the winding current and permanent magnet, and the torque in the magnetic gear relies on the interaction between multiple sets of permanent magnets. The winding current density of natural cooling motors containing permanent magnets usually does not exceed 6.5 A/mm^2 . Rare earth permanent magnets, which can be represented by equivalent windings, have higher current density [2, 3]. Therefore, under the same cooling conditions, magnetic gears can achieve higher torque density than conventional motors [4]. At present, the more feasible topology is coaxial planetary magnetic gear. The device has a simple structure. Under natural cooling conditions, and it can reach a torque density of $239 \text{ kN}\cdot\text{m/m}^3$ [5]. However, the main problem of this magnetic gear is that the mechanical strength of the magnetizing ring is low due high torque and radial force [6, 7]. Compared with ordinary magnetic gear motors, planetary magnetic gear motors have the advantages of small mass, small size, large transmission ratio, large load carrying capacity, smooth transmission, and high transmission efficiency, and overcome the shortcomings of general magnetic gears [8, 12]. Permanent magnet gear motors can be divided into concentric magnetic gears and permanent magnet planetary gear motors. Among them, permanent magnet planetary gear motor has attracted more and more attention due to the significant advantages of power density, efficiency, high transmission ratio, and heat dissipation capacity, and is widely used in high drive torque and

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low speed applications [9]. All components of the concentric magnetic gear and permanent magnet planetary gear motor rotate around the same axis. The magnet of this structure has the highest utilization rate and better transmission torque value. It is the biggest breakthrough and representative one at present. According to the air gap direction and magnet magnetization direction, it can be divided into the following four structures: 1) Radial air gap structure: the air gap direction of this magnetic gear mechanism is arranged in the radial direction. 2) Axial air gap structure: The air gap direction of this magnetic gear mechanism is arranged in the direction of the rotating shaft. 3) Radial and axial structure: the air gap direction of this magnetic gear mechanism has both radius and rotation axis direction. 4) Magnetization variation structure: The air gap direction of this magnetic gear mechanism is arranged in the direction of radius or rotation axis [10].

Most traditional permanent magnet gear motor parameter design methods only consider the case where the pole shape is relatively regular, and the pole has no pole shoes, but they do not consider the optimal size problem in practical applications. Therefore, the design of the permanent magnet planetary gear motor has shortcomings in applications, such as the stator core material, and the number of coil turns is not fully utilized. This paper draws on the idea of a stator permanent magnet motor. Based on the planetary magnetic gear motor, the stator side uses hybrid excitation, and the magnetic planetary gear is integrated into the permanent magnet motor. A new type of stator hybrid excitation planet for the steering system is proposed. The magnetic gear motor overcomes the shortcomings of the existing magnetic gear structure and performance, and has the advantages of high reliability, strong torque transmission capacity, and large transmission ratio. At the same time, it can adjust the levitation force and power in real time as the working conditions change, improving motor efficiency. This paper focuses on the topological structure and working principle of the stator hybrid excitation planetary gear motor and uses the finite element method to carry out its basic structure, operating principle, air gap magnetic density analysis, positioning torque, transmission torque, and magnetic field calculation methods. A detailed analysis is done to demonstrate the rationality of the structure.

2. BASIC WORKING PRINCIPLE

The topology structure of the stator-hybrid excitation planetary magnetic gear motor proposed in this paper is similar to a mechanical planetary gear. The schematic diagram of the topology is shown in Figure 1. The entire permanent magnet planetary gear motor is divided into a motor driving part and a planetary gear transmission part. The two parts are magnetically isolated by the rotor core of the motor. It consists of five main parts, namely the stator, rotor (permanent magnet ring gear), permanent magnet sun gear, planet gear carrier, and permanent magnet planet gear.

The proposed planetary magnetic gear has three transmission modes [11]. In the first mode, the planetary carrier is the output gear, so the permanent magnet sun gear and permanent magnet ring gear are driving gears. Replacing the number of teeth of a mechanical gear with the number of pole

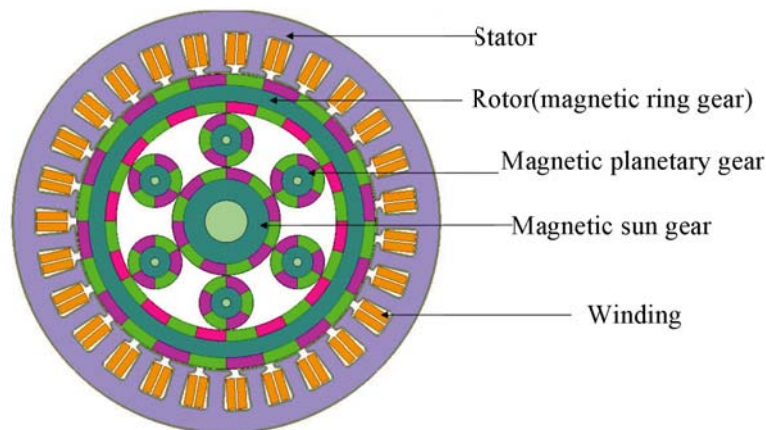


Figure 1. Stator hybrid excitation planetary gear motor.

pairs of a magnetic gear, the angular velocity relationship can be expressed as:

$$\omega_c = \frac{p_s}{p_s + p_r} \omega_s + \frac{p_r}{p_s + p_r} \omega_r \quad (1)$$

In formula (1), ω_s , ω_r , and ω_c are the angular velocities of the permanent magnet sun gear, permanent magnet ring gear, and planetary gear carrier, respectively. P_s , P_p , and P_r are the pole pairs of the permanent magnet sun gear, permanent magnet planet gear, and permanent magnet ring gear, respectively.

In the second mode, the permanent magnet sun gear is the output, so the permanent magnet ring gear and planetary gear carrier are the inputs, and the angular velocity relationship is,

$$\omega_s = \frac{p_s + p_r}{p_s} \omega_c - \frac{p_r}{p_s} \omega_r \quad (2)$$

In the third mode, the permanent magnet ring gear is used as the output, and the angular velocity relationship is

$$\omega_r = \frac{p_s + p_r}{p_r} \omega_c - \frac{p_s}{p_r} \omega_s \quad (3)$$

The reduction ratio is usually expressed by Equation (1). It can be known from Equation (1) that the reduction ratio is obtained by keeping the permanent magnet ring gear or the permanent magnet sun gear stationary. When $\omega_s = 0$ and $\omega_r = 0$, the expression of the reduction ratio is,

$$\frac{\omega_c}{\omega_s} = \frac{p_s}{p_s + p_r} \quad (4)$$

It can also be expressed as,

$$\frac{\omega_c}{\omega_r} = \frac{p_r}{p_s + p_r} \quad (5)$$

In the formula, P_r is larger than P_s . Therefore, Equation (4) produces a higher reduction ratio than Equation (5). Therefore, if a reduction ratio at high speed is required, it is best to keep the permanent magnet ring gear stationary.

3. FINITE ELEMENT ANALYSIS

In this section, the finite element method is used to calculate the electromagnetic performance and transmission performance of the stator hybrid-excited planetary magnetic gear motor, which mainly involves magnetic saturation, torque, pole shoe thickness, stator outer diameter, and coil turns. Table 1 lists the design data.

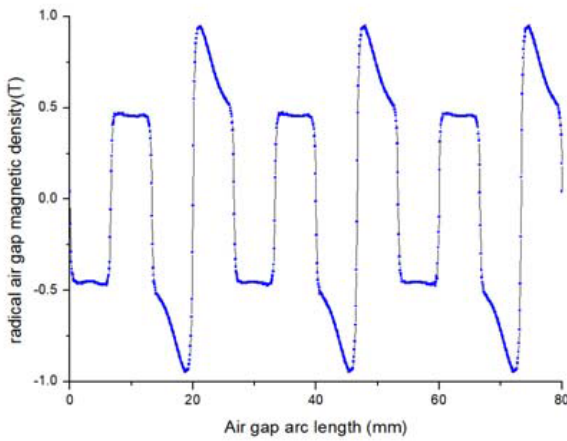
3.1. Air Gap Magnetic Density

Figures 2(a) and 2(b) are the air gap magnetic density between the permanent magnet sun gear and permanent magnet planet gear, and between the permanent magnet planet gear and permanent magnet outer ring gear. As shown in Figure 2(a), the permanent magnet sun gear and permanent magnet planet gear are external gears. At the narrowest air gap between the sun gear and planet gear, the peak air gap magnetic density is 1.0 T, corresponding to the permanent magnet sun gear. The permanent magnet planetary gear and permanent magnet outer ring gear in Figure 2(b) belong to internal meshing gears, and the permanent magnetic planetary gear and permanent magnet outer sun gear belong to external meshing gears. Similarly, the peak value of the air gap magnetic density at the narrowest point between the permanent magnets is 1.0 T, and there are air gaps between the planetary gear and outer ring gear, and between the outer ring gear and sun gear. The peak magnetic flux density of the internal teeth in Figure 2(c) is 1.0 T, and the peak magnetic flux density of the internal teeth in Figure 2(d) is 0.6 T. The peak magnetic flux density of the planetary teeth in Figure 2(e) and the tangential magnetic flux density of the planetary teeth in Figure 2(f) are 0.2 T. The above air-gap magnetic density waveform shows that the parameter setting of this type of magnetic gear is reasonable; the magnetic regulation performance is consistent with the working range of permanent magnets; and the magnetic regulation performance is better.

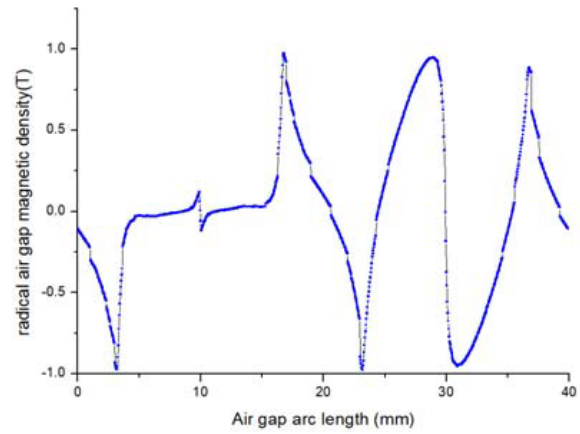
3.2. Transfer Torque and Positioning Torque

In the field of magnetic gear transmission, the maximum static torque or output torque is an important parameter to control the performance of magnetic gears. Therefore, by finely adjusting the thickness of the ring gear pole shoes and planetary ring gear pole shoes, the maximum static torque of the magnetic gear can be optimized. As shown in Figure 3(a), the thicknesses of the ring gear pole shoes are 0.7 mm and 1.3 mm. The inflection points appear, and the corresponding torques are 10.24 Nm and 10.16 Nm. As shown in Figure 3(b), the inflection points of the planetary ring gear pole shoes are 0.7 mm and 1.4 mm thick, and the corresponding torques are 8.27 Nm and 10.16 Nm, respectively. The torque changes periodically with the position angle, which is consistent with the working characteristics of magnetic gears.

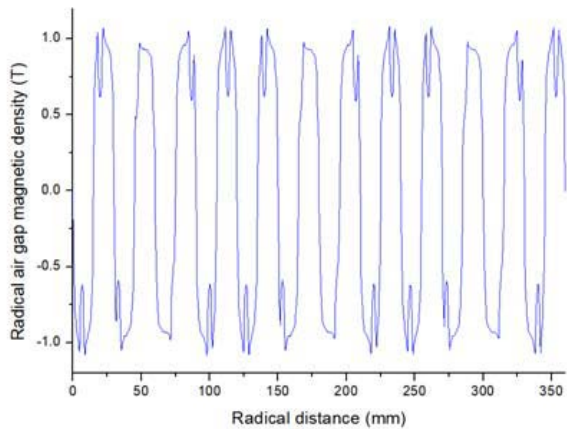
When the magnetic gear with strong magnetic coupling is in an equilibrium position and is set to rotate in a certain relationship, the positioning torque curve of the magnetic gear can be obtained. The torque transmitted by the permanent magnet sun gear and the permanent magnet planet gear is closely related to the current and position angle. According to the design parameters of the prototype, the current range is 5 ~ 20 A. When the current is 5 A and the position angle of the permanent magnet sun gear, permanent magnet planetary gear, and magnetic outer ring gear changes within the range of 0° to 30° , the positioning torque changes with the current and position angle. In order to obtain the positioning torque characteristic curve of the permanent magnet planetary gear, the permanent magnet planetary gear is set to a static state during the simulation, and the permanent magnet sun gear and permanent magnet outer ring gear rotate two pairs of magnetic pole lengths from the center of the gear train to obtain the moment angle characteristic curve of a period. As shown in Figure 3(c), due to the superiority of the internal meshing of the permanent magnet planetary gear, the peak value of its



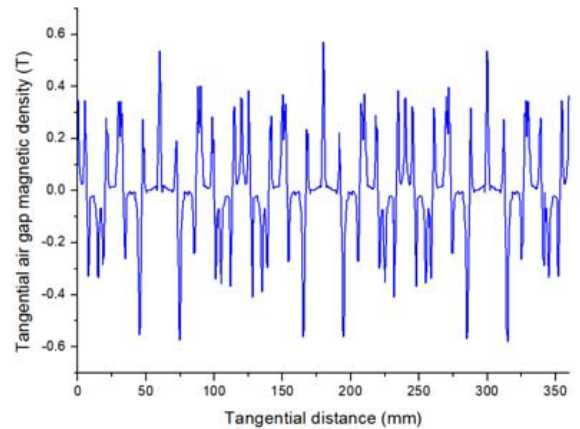
(a)



(b)



(c)



(d)

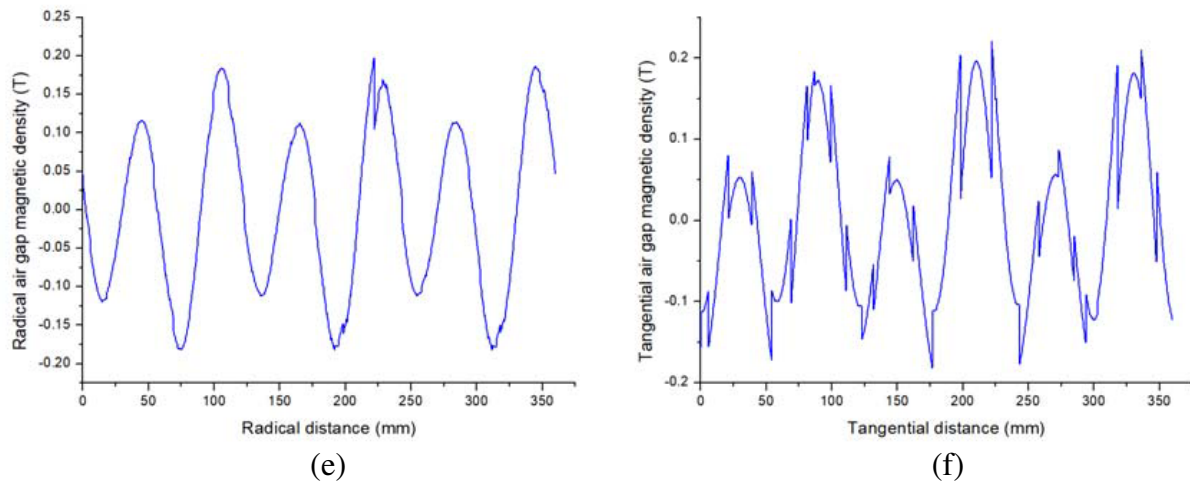


Figure 2. Air gap magnetic density: (a) Air gap magnetic density of permanent magnet sun wheel; (b) Planetary air gap magnetic density; (c) Radial magnetic density of internal teeth; (d) Tangential magnetic density; (e) Planetary teeth radial magnetic density; (f) Planetary tangential magnetic density.

Table 1. Key specifications and dimensions of the machine.

Quantity	Parameters
Based speed nb (rpm)	1000
magnetic planet gear center diameter (mm)	38.5
Inner Diameter of Stator (mm)	70.6
Outer Diameter of Stator (mm)	100
PM material	NeFe35
Number of turns per coil	50
Gear ratio	1 : 4 : -2
stator punching material	DW310-35
Airgap of machine (mm)	1
Pole-pairs of magnetic sun gear	6
Pole-pairs of magnetic planet gear	3
Pole-pairs of magnetic outer rotor	24
Pole-pairs of Inner tooth magnetic steel	12
PM height of magnetic sun gear (mm)	2.5
PM height of magnetic ring gear (mm)	2.5
PM height of magnetic planet gear (mm)	2.5

positioning torque reaches 0.020 N·m. Therefore, the proposed configuration can roughly maintain the maximum static torque.

The positioning moment of the permanent magnet sun gear is shown in Figure 3(d). The peak value of the positioning torque is 0.17 N·m, which is only 1/9 of the maximum transmission torque of the permanent magnet planetary gears, further verifying the rationality of the structure.

3.3. Current and Magnetic Density

As can be seen from Figures 3(c) and 3(d), the permanent magnet sun gear and permanent magnet planetary gear have many pairs of magnetic poles, so the positioning torque waveform has large burrs, but its periodicity is still good and has good sine wave characteristics. When the position angle is

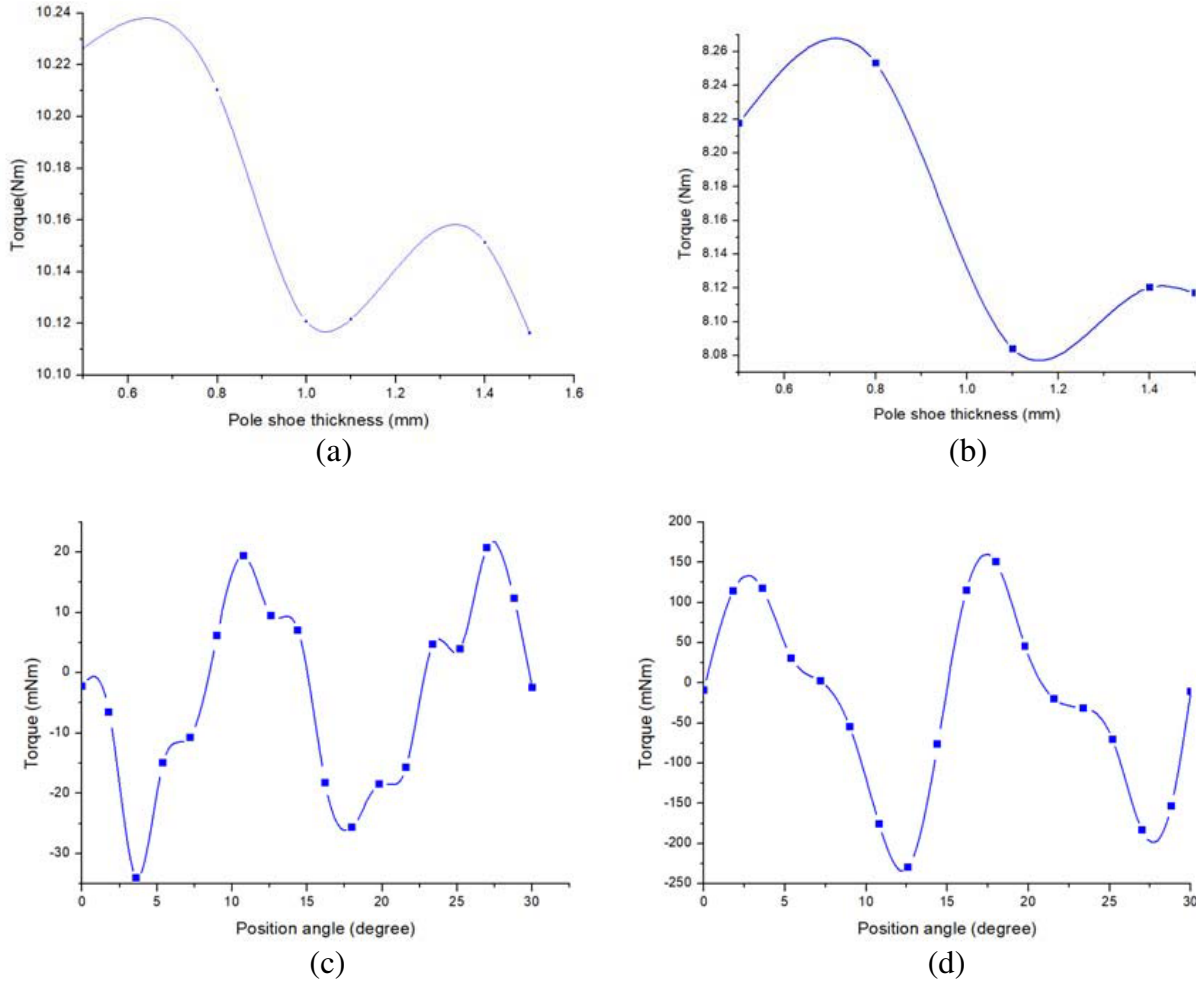


Figure 3. Transfer torque and positioning torque: (a) Ring gear torque; (b) Planetary ring gear torque; (c) Positioning torque characteristics of permanent magnet planetary gears; (d) Positioning torque characteristics of permanent magnet sun gear.

changed in the range of 0° to 30° , the three-phase current change range is sine periodic change in the range of 0 to 5 A, as shown in Figure 4.

3.4. Loss

According to the above analysis, when the rotation speed is set to 1000 rpm, the losses of each part of the magnetic gear are shown in Figure 5. The core loss is basically zero, and the copper loss (solid loss) changes with time and shows a periodic change. The maximum is 200 w. This is mainly due to the presence of harmonic components with high rotational speed in the air gap, which will cause considerable eddy current losses in the permanent magnet material. In order to reduce the permanent magnet loss, a method of dividing the permanent magnet into several pieces along the circumferential direction is adopted. However, this method will also bring some difficulties to the mechanical assembly.

3.5. Magnetic Field Analysis

By selecting the thickness of the stator pole shoes, the number of turns of the stator coil, and the outer diameter of the stator, a reasonable magnetic gear transmission mechanism was obtained, and the theoretical design results were simulated. The analysis of the magnetic field lines and magnetic

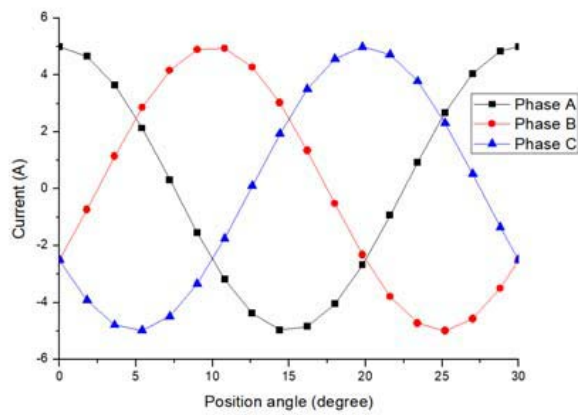


Figure 4. Three-phase current.

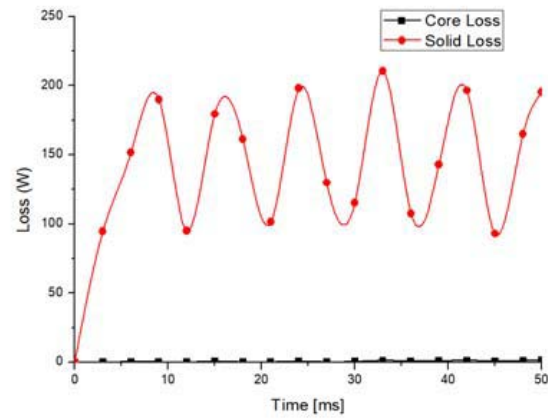


Figure 5. Loss relationship.

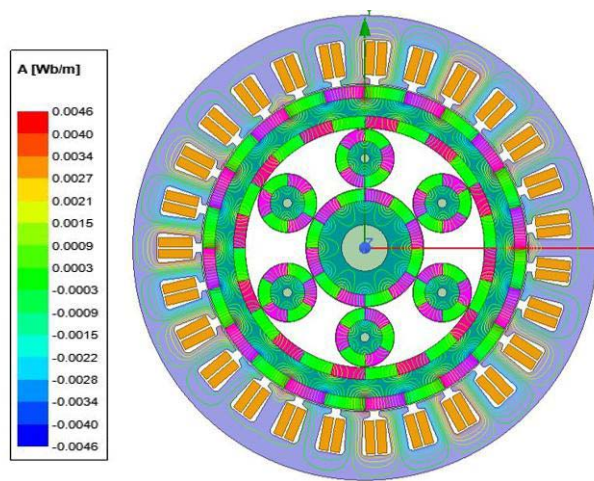


Figure 6. Magnetic field lines.

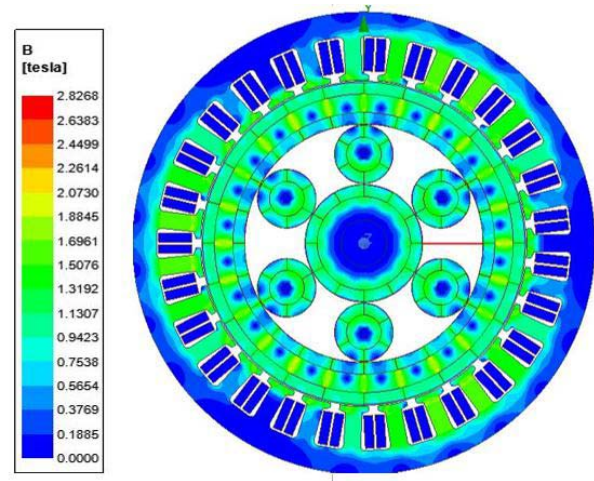


Figure 7. Magnetic flux density distribution.

flux density distribution was obtained from Figure 6 and Figure 7 which are magnetic field line and magnetic flux density distribution diagrams of a magnetic gear motor, respectively. As can be seen from the figure, the magnetic field between the permanent magnet sun gear and permanent magnet planetary gear is relatively independent, and the magnetic coupling between the two parts is very low. The maximum magnetic induction strength is about 1.1 T, which is in line with the working range of permanent magnets and helps to achieve the ideal state. The transmitted torque verified the rationality of the initial design.

4. EXPERIMENTAL VALIDATION

In order to validate the theoretical analysis, a prototype machine with unskewed rotor is built and tested, as shown in Figure 8. The test results on this prototype machine can be used as the validation of the FE analysis. The measured and predicted transmitting torques are compared in Figure 9 with satisfactory agreement.

A prototype of stator-hybrid magnetic planetary gear motor has been built to validate the theoretical analysis results. The experimental results on the prototype machine show that the measured transmitting torque closely agree with the predicted transmitting torque. The maximum output torque of this motor is about 21 Nm, and its characteristic is that it has speed closed-loop control characteristics, which can output large torque at low speed.

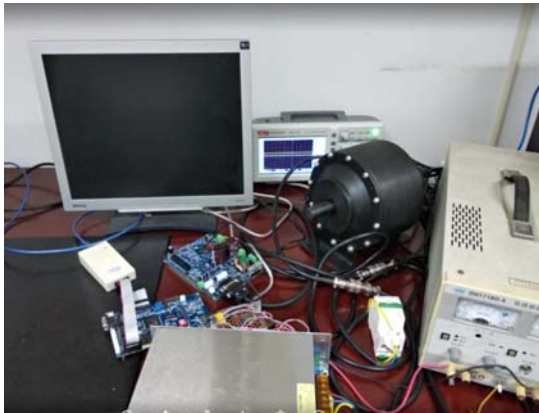


Figure 8. The experimental system of the applied prototyped machine.

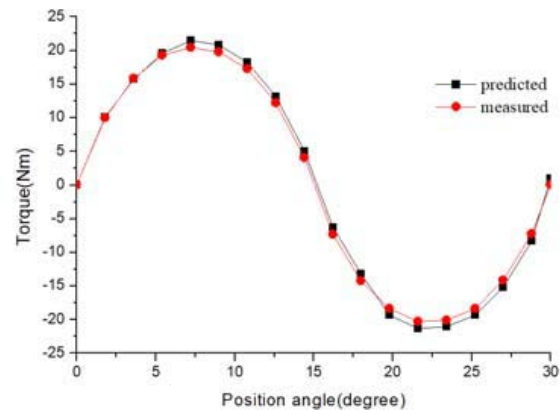


Figure 9. Torque-angle characteristics between the predicted and measured designs.

5. CONCLUSION

This paper proposes and implements a stator hybrid field planetary magnetic gear motor, which has the obvious advantages of higher mechanical integrity and reduced PM material, while maintaining the torque transmission capability. The basic structure, operating principle, air-gap magnetic density analysis, positioning torque, transmission torque, and magnetic field calculation method are analyzed in detail, and the rationality of the structure is demonstrated through experiments. The prototype of the stator-excitation planetary magnetic gear motor is still under further research, and more detailed experiments will be carried out on the prototype soon. The next step is to develop the oblique type of the stator-excitation planetary magnetic gear motor adjusting magnet core on this basis, so as to reduce the stagnation torque of stator-excitation planetary magnetic gear motor, and use 3D printing to break through the limitations of the traditional processing machine to complete the oblique prototype verification of magnetic core adjustment.

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