The design method of a novel magnetic suction gear reducer

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Abstract. There are some shortcomings for the ordinary gear transmission such as friction, noise, low efficiency and so on; with the contactless magnetic coupling transmission, these can be weakeness greatly. This paper introduces the development course of the traditional various transmission method to further illustrate the possibility and characteristics of single-side coupled of rare earth permanent magnets used as gear teeth for magnetic suction gears.it also introduces the basic design principles of the internal and external meshing magnetic gears and the calculation of the transmission torque in gear is coupled. Through the quantitative analysis of the experimental data, the relationship between the transmission torque of the magnetic gear and the relative rotation angle, working airgap, flux leakage is obtained. Finally, the relevant conclusions and formula for calculating torque of magnetic suction gear reducer design criteria are obtained.

1. Introduction

Gear transmission is extremely versatile, but its basic form of transmission has not changed for a long time, both of which are driven by mechanical meshing of gear teeth of two gears. Therefore, there are some problems that cannot be eliminated in the gear transmission, such as mechanical fatigue, gear wear, vibration noise. People are trying to find new ways to solve these problems by using the lubrication technology, yet the problem still exists.

The magnetic drive device is based on magnetic theory and it uses a magnetic field to penetrate a certain working air gap to complete torque-free contact through magnetic coupling. The traditional mechanical drive is different from the main drive torque, non-contact engagement of driven rotor with no wear, zero leakage and other characteristics of the earliest successful application of magnetic pumps to achieve a toxic or corrosive liquid or gas leak-free delivery. With the advent of rare earth permanent magnet materials and the development of magnetic drive technology, various forms of permanent magnet coupler drive mechanisms such as permanent magnetic clutches, magnetic couplings and permanent magnet motors have been used in petroleum, chemical, pharmaceutical and textile industries such as the transmission of special transmission requirements of the occasion [1].

However, little research has been done on the application of magnetic drive mechanism to variable speed transmission. The new magnetic gear drive technology proposed by early scholars in Japan pioneered the research direction of using rare earth permanent magnet material in the field of mechanical transmission. The magnetic drive of this structure adopts the conventional external gear structure, the principle of N/S opposite-phase attraction is used to achieve a non-contact, frictionless drive. However, the excessively large curvature of the air-gap, thus failing to achieve a large torque transmission required in engineering. At the beginning of this century, Institute of Electrical
Engineering of the Chinese Academy of Sciences also conducted relevant research on permanent magnet gears, and conducted a large number of experimental analysis for the specific structure [2, 3]. According to non-contact magnetic coupling with non-magnetic material consisting of closed space transmission power characteristics, the theoretical research on the related magnet transmission mechanism as the driving device of the artificial heart was carried out.

In this paper, the concept of magnetic suction gear is introduced to the magnetic variable speed drive. The mathematical model and experiment are used to analysis the influence factors of the transmission torque. The most effective design scheme and conclusion of magnetic suction gear reducer design are obtained.

2. Magnetic suction gear design

2.1. Working principle of magnetic suction gear

Figure 1 shows the magnetic suction gear is suitable for internal and external gear. The magnetic field lines formed in the axial gap of the meshing area of the driving wheel and the driven wheel have magnetic coupling teeth. The magnetic profile can be coupled without gear contact and the driven gear transmits power by the cycle of generation → increase → decrease → disappearance as the area of coupling with the capstan in the meshing region increases with the rotation of the gear role.

![Figure 1. Gear meshing of magnetic suction.](image1)

The gear tooth profile made of rare materials in earth are NdFeB. Each tooth has an N (S) pole [4]. Bull gear and pinion are designed as single-sided tooth. Multi-faceted profile can effectively mesh and increase the gear transmission torque. Magnetic suction gear transmission is through the magnetic gear coupling, the magnetic force generated by the meshing through the drive wheel and driven gear tooth surface continuous directional coupling to make the drive to achieve fixed speed ratio.

2.2. Internal meshing magnetic suction gear basic design

Figure 2 shows the magnetic suction gear meshing bull gear and pinion design of the basic parameters are as follows: the size of the gear teeth are \( Z_1 \) and \( Z_2 \), modulus \( m \), the relative angle difference \( \varphi = (\varphi_1 - \varphi_2) \), the gear transmission ratio is \( i \).

![Figure 2. Internal and external meshing magnetic suction gear basic design.](image2)
Pinion angle $\phi_1$, bull gear angle $\phi_2$, so the result is as follows:

Relative rotation angle difference: $\varphi = (\phi_1 - \phi_2)$ (2)

The gear transmission ratio: $i = Z_1 / Z_2$ (3)

Such as the magnetic suction gear adjacent teeth magnetic N,S,N,S ...... arranged, $Z_1$, $Z_2$ must be even. When the size of the gear is odd number of teeth, the pinion magnetic N (S) pole, then the magnetism of the gear into S (N) pole [5-7].

2.3. external meshing magnetic suction gear basic design

Figure 2 shows the external meshing gear of magnetic suction gear, the pinion and the bull gear mesh with the center distance change can be obtained external meshing drive. Taking the engagement pressure angle $\alpha$ and the center distance $L_2$ as parameters, the equations can be obtained as follows.

3. Experimental analysis

3.1. Magnetic suction gear drive mechanism of the main parameters

Torque transmission performance test of the simple device by a pinion and 2.2kW DC motor connected by the silicon rectifier speed control. According to the center shift degree and the axial gap of the pinion and the bull gear, the performance test is carried out. The active wheel permanent magnet material: NdFeB, $B_r = 1.25T$, $\mu_r = 1 \times 10^5$ gear structure size: the basic radius of the pinion: $r_{b2} = 5cm$, tooth height: $h = 2cm$ tooth width $w = 2.5cm$, tooth thickness $L_m = 0.8cm$, $Z_2 = 9$ base circle radius: $r_{b1} = 7cm$ tooth height: $h = 2cm$ tooth width: $w = 2.5cm$, tooth thickness: $L_m = 0.8cm$, $Z_1 = 18$. Bull gear connected to the torque meter (200Nm range), the load by the electromagnetic brake.

3.2. Transmission torque and the relative angle of the relationship

The dynamic transmission performance test is to measure the torque of the bull gear (T, N.m) with the coupling air gap ($L_g=5mm$ interval), the speed of the pinion ($N=100r/min$ interval) and the central deviation of the outer meshing ($e=14mm$ interval). Figure 3 shows the relationship between the relative rotational angle difference of the pinion and the bull gear and the transmission torque. It is obvious from Figure 3 that the moment occurred at the intersection of the curves.

![Figure 3. Bull gear and small pinion relative rotation angle $\varphi$ and the relationship.](image)

In the ideal state, the magnetic flux leakage coefficient and the magnetic reluctance coefficient are 1. When the relative rotation angle difference is $0^\circ$, the torque of the drive load also is 0. With the increase of the deflection angle, the torque of the transmission load also increases. After reaching a limit value, it decreases. It can be seen from the Figure 8 that when the relative rotation angle difference is about $5^\circ$, the torque of the transmission load of magnetic suction gear is the optimal.
3.3. Transmission torque and the relationship between the coupling air gap

In the ideal state, when the magnetic flux leakage coefficient $K_f=4$ and the magnetic reluctance coefficient $K_r=1$, the relative rotation angle difference of the magnetic suction gear is $5^\circ$, the relationship between the transmission torque load and the coupling air gap is shown in Figure 4.

With the increase of working air gap, the torque of load is transmitted decreases rapidly and then decreases slowly. It is concluded that the air gap more little has more influence on the transmission torque, and the working air gap is smaller the torque of load transmission performance would be better, so the air gap is reduced as much as possible while meeting the gear transmission performance.

![Figure 4. The size of the gear coupling airgap $L_g$ and the transmission torque $T$ relationship.](image)

3.4. Transmission torque and magnetic flux leakage relationship

The magnetic reluctance coefficient of magnetic suction gear is related to the properties of rare earth materials, and its parameters are fixed values after the material of gear was choosen [8-10]. But the magnetic flux leakage is related to the location of the gear coupling.

In the ideal state, the reluctance coefficient takes 1, the reluctance coefficient $K_r=1$, the gear relative angle difference $\varphi=5^\circ$, the working air gap $L_g = 5\text{mm}$, the value of the leakage magnetic coefficient ranges from 0~80. The relationship between the torque of the transmission and the magnetic flux leakage coefficient shown is in Figure 5. It can be seen from the figure that with the increase of the magnetic flux leakage coefficient, the torque is transmitted from 0 to 20 rapidly decreases and then becomes a steady trend. Therefore, a reasonable design of the gear mechanism to reduce magnetic flux leakage is particularly important for the torque of load is transmitted by coupling.

![Figure 5. Gear magnetic flux leakage $K_r$ and the transmission torque $T$ relationship.](image)
4. Mathematical model analysis and calculation of transmission torque

In the stationary state, the relative rotation angle difference of the magnetic suction gear transmission mechanism is $0^\circ$. At this time, the magnetic field intensity at the action surface of the permanent magnet gear teeth is $H_1$, and the magnetic induction intensity is $B_1$, as shown in Figure 6.

![Figure 6. Mathematical model of ideal demagnetization rate.](image)

When the magnetic suction gear is driven by the motor, the relative rotational angle difference of the bull gear with the pinion is $\varphi$. At this time, the magnetic field strength at the action surface of the permanent magnet gear teeth is $H_2$, and the magnetic flux intensity is $B_2$. Meanwhile, $W$ is the work done by the drive torque of the magnetic suction gear is calculated as follows.

$$W = S_{shadow} \times V_\alpha = B_1 (H_2 - H_1) \times V_\alpha$$  \hspace{1cm} (4)

Under the ideal condition, $B$ is the permanent magnet demagnetization curve of the magnetic flux density, the magnetic permeability of vacuum is expressed as $\mu_0 = 4\pi \times 10^{-7}$ [11-13], $K_f$ and the $K_r$ respectively are the magnetic flux leakage coefficient and the magnetoresistance coefficient of the bull gear and pinion relative rotation, $\mu_r$ is the magnetic media relative permeability, magnetic flux density $B_1$ and $B_2$ are calculated as follows:

$$B_1 = B_r - \mu_r \mu_f H_1$$  \hspace{1cm} (5)

$$B_2 = B_r - \mu_r \mu_f H_2$$

$$\mu_f = \frac{K_f}{K_r}$$  \hspace{1cm} (6)

In the stationary state, the magnetic flux $\Phi$ and magnetic field force $F$ is calculated as follows:

$$\Phi = B_m S_m = K_f B_g S_g$$  \hspace{1cm} (7)

$$F = H_m L_m = K_f H_g L_g$$

In the formula, $L_g$ is the working air gap of the bull gear and pinion, $L_m$ is the thickness of the teeth of the magnetic suction gear, $S_m$ as parameter of the area of the magnetic field and the surface of the permeable magnetic material, $S_g$ as parameter of the area of the coupling surface of the magnetic gear, $H_m$ as parameter of the magnetic field and magnetic material at the magnetic field intensity at the surface, $B_m$ as parameter of the magnetic field and material at the magnetic induction intensity.

The formula uses SI unit system, $F$, $B_m$, $H_m$, $S_m$ units were N, T, A/m, m$^2$ [14].

When the pinion gear relative to the bull gear angle difference is $\varphi$, the magnetic gear teeth through the path is $L$.

$$L = \sqrt{(L_g^2 + 2r \sin \varphi)^2}$$  \hspace{1cm} (8)

When the gear is driven, the magnetic induction of each gear and magnetic field force $F$ is calculated as:

$$H_m L_m = K_f H_g \sqrt{(L_g^2 + 2 \sin \varphi)^2}$$  \hspace{1cm} (9)
\[ B_m = \mu_i \frac{\mu_0 H_m L_m}{L_g} \]  

When the gear rotates, the work done from one coupling surface to the other is \( W \), the transmission torque is \( T \). \((V_m \text{ is the gear tooth volume})\)

\[ W = B_l (H_1 - H_2) \times V_m \]

\[ T = \frac{\partial W}{\partial \phi} \]

\[ T = \frac{1}{2} \frac{V_m}{4 \mu_i r} \times B_l^2 \times \mu_i \times \frac{r^2 L_m \sin \phi}{L(L_g + \mu_i \times L_m)^2} \]

\[ T = \frac{1}{2} \frac{V_m}{4 \mu_i r} \times B_l^2 \times \mu_i \times \frac{r^2 L_m \sin \phi}{L \sqrt{L_g + (r \sin \frac{\phi}{2})^2} \sqrt{(L_g + (r \sin \frac{\phi}{2})^2 + \mu_i \times L_m)^2}} \]

5. Comparison between the calculated and experimental data

Magnetic suction gear coupling at different transmission ratio corresponding to the different leakage coefficient, different coupling air gap corresponding to the flux leakage is also different, with different leakage magnetic flux leakage coefficient and the calculated value of the gap shown in Table 1.

**Table 1. Different magnetic flux leakage and coupling condition calculated transmission torque.**

| \( L_g (\text{mm}) \) | 3 | 5 | 7 | 8 | 10 |
|----------------------|---|---|---|---|----|
| K=1                  | 248 | 182 | 122 | 94 | 65 |
| K=2                  | 199 | 151 | 109 | 88 | 64 |
| K=3                  | 159 | 122 | 92 | 79 | 58 |
| K=4                  | 132 | 103 | 77 | 72 | 51 |
| K=5                  | 112 | 88 | 67 | 60 | 45 |

**Table 2. Transmission torque of different air gap relative error of the measured and calculated.**

| Air gap (mm) | Torque measured value (N.m) | Torque calculated value (N.m) | Error% |
|-------------|----------------------------|-------------------------------|--------|
| 3           | 130                        | 132                           | 1.5    |
| 4           | 113                        | 115                           | 1.8    |
| 5           | 100                        | 103                           | 3.3    |
| 6           | 89                         | 92                            | 2.5    |
| 7           | 79                         | 77                            | 2.9    |
| 8           | 70                         | 72                            | 3.2    |
| 9           | 62                         | 64                            | 4.5    |
| 10          | 54                         | 51                            | 1.8    |

As can be seen from Table 2, through establish a mathematical model of the magnetic suction gear transmission and experimental analysis, when the flux leakage coefficient \( K_r = 4 \), the relative error of the torque measured and calculated is about 3% When the gap is the minimum.

6. Conclusions

Magnetic suction gear design concept of magnetic suction gear is based on the single-sided coupling of gears along the transverse magnetic field. According to the experimental analysis, the coupling air...
gap of the gear is reduced as much as possible during the working. Increasing the torque density of the magnet teeth by increase the gear teeth to improve the magnetic transmission gear torque performance.

When the magnetic gear is non-contact and meshed in overload, the bull gear and pinion are slipping and the drive relationship is cut off, no noise and wear, and high transmission efficiency. It is also possible to achieve coupling on both sides and multiple transmission of gear ratio. Internal and external magnetic suction gear meshing can adjust the axial position and fixed to change couple air gap and couple area of the gear or change the gear tooth thickness to change the size of the transmission torque, while single-sided couple can achieve positive or reverse.

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