Torque analysis of electromechanical integrated electromagnetic worm drive

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Abstract. In this thesis, based on the electromagnetic theory, the mechanical model of worm wheel and worm mesh was established with electromagnetism worm drive, force analysis of electromagnetism worm drive was proceed, the formula of the system output torque was derived, and torque change rule with different parametric was researched. Results show, the system torque output also increases when the number of teeth increases; The output torque of the system increases with the increase of \( R \), and shows a slowly increasing saturation phenomenon; The electromagnetic worm drive has overload protection function; The number of worm wheel teeth increases, so that the output torque of the system increases; The \( \omega / R \) is better to evaluation between 2 and 5 in the actual design; The evaluation of \( R \) should be considered as the evaluation of \( \omega / R \). The results provide theoretical basis for the manufacturing and further research on the properties of the drive.

1. Introduction

With the progress and development of modern industry, the magnetic driving technology has been further studied on the basis of previous achievements, and it has developed greatly and has been applied in many industries [1]. The non-contact magnetic wheel and its theory were proposed by Japanese scholar Ikuta in 1991, which can solve some problems such as noise and wear caused by wheel transmission [2]; Later, H. Zhou et al wrote the paper in 2001 to discuss the controllable planar five-bar mechanism, and used the best comprehensive method to solve it [3]; Domestic research on mechanical and electrical integration super torus transmission has made many achievements, professor Xu Lizhong derived drive mechanism, kinematics principle of the mechanism and stress analysis, the discussion analyses the torus stator tooth and planetary wheel teeth by stress and strength checking formula is given, and carry out the research of control theory and control technology [4-6]; Professor Zhao Han studied the rare earth permanent magnet wheel and did a lot of work on the magnetic field and torque calculation of permanent magnet wheel transmission mechanism [7-8].

In this thesis, the parameter design and torque analysis of mechanical and electrical integration electromagnetic worm transmission mechanism was carried through, the transmission is a kind of use of the characteristics of the magnet, combined with the electrical machinery, electromagnetism and mechanics and developed a new type of non-contact transmission form - electromagnetic worm drive, electromagnetic worm drive is a kind of generalized compound motion, no contact, it is integrated with worm drive and motor function, further enhances the function of worm wheel and worm drive, has extensive practical application value. The driver is characterized by ring surface of a rotating...
magnetic field generated worm drive with multiple permanent magnets for tooth worm wheel rotation, so as to drive the worm wheel output shaft rotary and realize the power of low speed high torque output [9].

2. Operating principle
As shown in figure 1, the structure diagram of electromechanical integrated electromagnetic worm drive is mainly composed of worm wheel system, worm system and bracket. On the circumference of the worm wheel, the permanent magnet of N pole and S pole is arranged evenly. The size, shape and layout of the permanent magnet are selected according to the actual needs. The center worm is assembled by silicon steel sheet, and the electromagnetic coil on the periphery of the center worm is spiral uniform distribution. The device combines worm drive and electromagnetic transmission to form a new type worm wheel transmission mechanism [10-11].

3. Force analysis
Force analysis diagram as shown in figure 1 of electromagnetic worm drive, the ring surface worm meshes with the worm wheel tooth in any corner \( \phi_1 \), which is the magnetic force of the rotating magnetic field generated by the permanent magnet of the worm wheel and the electric coil on the ring surface worm. The rotating magnetic field generated by the permanent magnet of worm wheel and the coils on the toroidal worm has a magnetic force at the engagement point. \( F_{ni} \) represents the magnetic force of the worm wheel at the moment, which is the normal force. \( F_{ti} \) and \( F_{ai} \) respectively represent its tangential component and axial component. According to the theory of electromagnetism, current carrying conductor \( L \) gets magnetic field force \( F \) in the magnetic field \( B, F = BIL \). In electromagnetic worm drive system, using equivalent macroscopic current instead of the magnetism of permanent magnet material itself, then you can get magnetic field effect force between the worm and worm wheel namely, shown in figure 1 of normal force \( F_{ni} \), its computation formula is as follows

\[
F_{ni} = BLI_d
\]  

(1)

Where in \( B \) ——The superposition magnetic field strength of armature rotating magnetic field and worm wheel permanent magnet field (T);  
\( L \) ——The effective length of the worm permanent magnet (mm);  
\( I_d \) ——The equivalent current strength of worm wheel permanent magnet (A);  

According to the theory of electromechanics, can get to know

\[
I_d = \frac{\pi}{2} K_f F_o
\]  

(2)

Where in \( K_f \) ——excitation magnetic potential form factor;  
\( F_o \) ——Equivalent excitation potential (ampere-turn).
When $K_f = 4/\pi$, substitute $4/\pi$ into equation (2)

$$I_d = 2F_0$$

(3)

And because

$$F_0 = \frac{L_0B_0}{\mu_0}$$

(4)

Where $\mu_0$—air permeability (H/m); $L_0$—width of air gap (mm); $B_0$—worm wheel permanent magnet magnetic induction intensity (T).

The formula (4) is substituted into equation (3)

$$I_d = \frac{2L_0B_0}{\mu_0}$$

(5)

Equation (5) is substituted into equation (1) to obtain the normal force formula between worm wheel and ring surface worm

$$F_n = \frac{2L_0B_0}{\mu_0}$$

(6)

As shown in figure 1, the normal force $F_n$ can be decomposed into axial component $F_{ai}$ and tangential component $F_{ti}$, and its calculation formula is as follows.

$$\begin{cases}
F_{ai} = F_n \sin \lambda_i \\
F_{ti} = F_n \cos \lambda_i
\end{cases}$$

(7)

In the calculation formula $\lambda_i$—ring surface worm lead angle ($^\circ$).

4. System output torque

In the electromagnetic worm drive, the worm wheel meshing in the ring surface worm is affected by the axial component $F_{ai}$ and tangential component $F_{ti}$ in the vertical direction of the plane. In the electromagnetic worm drive, the worm wheel gets the driving torque $T_i$ in the ring surface worm is provided by tangential component $F_{ti}$. If the output torque of worm wheel is $T_n$, and the calculation formula of the output torque of the system is [12-14].

$$T_n = \sum_{i=1}^{Z_n} F_n \cos \lambda_i R \left( \frac{a}{R} - \sin \varphi_i \right)$$

(8)

In the formula, $a$ is the center distance of worm wheel and worm, and $R$ is the worm radius.

Equation (7) is substituted into equation (8)

$$T_n = R F_n \sum_{i=1}^{Z_n} \cos \lambda_i \left( \frac{a}{R} - \sin \varphi_i \right)$$

$$= RF_n \sum_{i=1}^{Z_n} \cos \lambda_i \left( \frac{a}{R} - \sin \varphi_i \right)$$

(9)

Transmission ratio of electromagnetic worm drive in electromagnetic worm drive system...
\[ i = \frac{\omega_2}{\omega_1} = \frac{Z_1}{Z_2} = \frac{Z_1}{2p} \]  

(10)

The condition that the transmission proper meshing needs to satisfy is

\[ \theta_2 \lambda_i = \frac{Z_2}{Z_1} \left( \frac{a}{R} - 1 \right) = \frac{2p}{Z_1} \left( \frac{a}{R} - 1 \right) \]  

(11)

In the formula, \( p \) is the logarithm of worm pole, and \( Z_1 \) is the worm wheel number.

The formula (1) and (11) is substituted into equation (9)

\[ T_s = RF \left[ \frac{Z_2}{Z_1} \left( \frac{a}{R} - 1 \right) \sum_{i=1}^{j} \sin \left( \frac{a}{R} - \sin \phi_i \right) \right] = \]

\[ BLI R \left[ \frac{Z_2}{Z_1} \left( \frac{a}{R} - 1 \right) \sum_{i=1}^{j} \sin \left( \frac{a}{R} - \sin \phi_i \right) \right] = \]

\[ \sqrt{\frac{2p}{Z_1} \left( \frac{a}{R} - 1 \right) + 1} \]  

(12)

5. Analysis of Examples

Initial selection of model parameters: worm wheel radius \( R = 60 \) mm, worm laryngeal radius \( r = 55 \) mm, the wrap angle of worm relative worm wheel is \( 90^\circ \), air gap is \( l_i = 0.2 \) mm, \( NI = 100 \) (ampere-turn), the laryngeal lead angle of worm is \( 55.58^\circ \), atmospherical magnetic conductivity is \( \mu_0 \), number of pole-pairs \( p = 1 \), \( B = B_0 = 1.32 \) T. The maximum and minimum output torque can be calculated.

According to the data and the above analysis, the system output torque of different magnetic poles can be drawn with the number of pole pairs \( p = 1 \), as shown in figure 2 ~ figure 7.

**Figure 2.** System output moment \(( z_i = 6, \ p = 1, \ i = 3)\).

**Figure 3.** System output moment \(( z_i = 8, \ p = 1, \ i = 4)\).
According to the output torque diagram of different number of worm wheels teeth, it can be seen that:

(1) Because the number of magnetic poles and the meshing angle are different, the number of meshing teeth is changing periodically, so the output torque of the system is changed in adder-like, and there exists the mutation point.

(2) The output torque of the system increases with the increase of the number of magnetic poles of worm wheels, so it can be seen that increasing the number of magnetic poles of worm wheels can increase the output torque of the system.

(3) From the angle of stable operation, the more worm wheels number, the more stable running, while $p = 1$, pole number of worm wheels is 8, 12, 16, 18, the mutation variable is small and stable. It can be used as the first data to determine the number of magnetic poles of worm wheel.

(4) Increasing the number of worm poles can increase the system output torque. But it is difficult to processing and manufacturing after increasing the number of magnetic poles of the worm.

(5) When $Z_i = 6$, number of pole-pairs $p = 1$, the maximum output torque is in the range of $-45° \sim -15°$ and $15° \sim 45°$, the angle range of the minimum output torque is $-15° \sim 15°$. 

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Figure 4. System output moment ($Z_i = 10, \ p = 1, \ i = 5$).  
Figure 5. System output moment ($Z_i = 12, \ p = 1, \ i = 6$).  
Figure 6. System output moment ($Z_i = 14, \ p = 1, \ i = 7$).  
Figure 7. System output moment ($Z_i = 16, \ p = 1, \ i = 8$).
(6) When \( Z_1 = 8 \), number of pole-pairs \( p = 1 \), the maximum output torque is in the range of \(-45^\circ \sim -42^\circ\), \(-3^\circ \sim -3^\circ\), \(-42^\circ \sim 45^\circ\), the angle range of the minimum output torque is \(-42^\circ \sim 3^\circ\), \(3^\circ \sim 42^\circ\), the system is mainly operated within the range of minimum output torque.

(7) When \( Z_1 = 10 \), number of pole-pairs \( p = 1 \), the maximum output torque is in the range of \(-45^\circ \sim -27^\circ\), \(-9^\circ \sim 9^\circ\), \(-9^\circ \sim 45^\circ\), the angle range of the minimum output torque is \(-27^\circ \sim -9^\circ\), \(9^\circ \sim 27^\circ\), the system is mainly operated within the range of minimum output torque, the system output torque varies periodically between the maximum and minimum values.

(8) When \( Z_1 = 12 \), number of pole-pairs \( p = 1 \), the maximum output torque is in the range of \(-45^\circ \sim -43^\circ\), \(-18^\circ \sim -15^\circ\), \(9^\circ \sim 12^\circ\), the angle range of the minimum output torque is \(-43^\circ \sim -18^\circ\), \(-15^\circ \sim 9^\circ\), \(9^\circ \sim 36^\circ\), the system is mainly operated within the range of minimum output torque.

(9) When \( Z_1 = 14 \), number of pole-pairs \( p = 1 \), the maximum output torque is in the range of \(-45^\circ \sim -32^\circ\), \(-19^\circ \sim -6^\circ\), \(7^\circ \sim 20^\circ\), \(33^\circ \sim 45^\circ\), the angle range of the minimum output torque is \(-32^\circ \sim -19^\circ\), \(-6^\circ \sim 7^\circ\), \(20^\circ \sim 33^\circ\), the system output torque varies periodically between the maximum and minimum values.

(10) When \( Z_1 = 16 \), number of pole-pairs \( p = 1 \), the maximum output torque is in the range of \(-45^\circ \sim -20^\circ\), \(-13^\circ \sim -13^\circ\), \(20^\circ \sim 45^\circ\), the angle range of the minimum output torque is \(-20^\circ \sim -13^\circ\), \(13^\circ \sim 20^\circ\), the system is mainly operated within the range of maximum output torque.

6. Analysis of influencing factors of output torque

According to equation (12), the parameters affecting the torque output are analyzed, and Figure 8 is a variation of torque following \( Z_1 \); Figure 9 is a variation of torque following \( i \); Figure 10 is a variation of torque following \( \omega \); Figure 11 is a variation of torque following \( a \); Figure 12 is a variation of torque following \( R \); Figure 13 is a variation of torque following \( a/R \). These graphs are the curve of the change in two teeth meshing.

From those pictures:

1. The output torque \( T_1 \) of the system increases with the increase of transmission ratio \( i \), which is because the increase of system transmission ratio means the increase of worm wheel number and the increase of torque output of the system. The system torque output also increases when the number of teeth increases.

2. The output torque \( T_1 \) of the system increases with the increase of \( Z_1 \), and shows a slowly increasing saturation phenomenon. When \( Z_1 = 18 \), the decrease trend appears.

3. The output torque \( T_1 \) of the system decreases with the increase of position angle \( \omega \) in worm meshing point, it stays the same when it goes down to a particular angle. When the calculation position Angle \( \omega = 0 \), the worm wheel and the worm are meshed at the moment when the two teeth are fully meshed and at the maximum output moment point. When a certain value is reached, the output torque of the system will no longer be increased, which is within the range of the minimum output torque. It can be seen that the electromagnetic worm drive has overload protection function.

4. The output torque \( T_1 \) of the system increases with the increase tendency of center distance \( a \), Because the increase of center distance also means that the diameter of worm wheel increases, that is, the number of worm wheel teeth increases, so that the output torque of the system increases.
(5) The output torque $T_n$ of the system increases with the increase of $a/R$. When $a/R = 5$, it reaches the maximum value and then slowly decreases. Therefore, it is better to evaluation between 2 and 5 in the actual design.

(6) The output torque $T_n$ of the system decreases rapidly with the increase of radius $R$, in other words, the increase of worm radius will make the output torque of the system decrease very quickly. Therefore, in the actual design, the evaluation of $R$ should be considered as the evaluation of $a/R$. 
7. Conclusions
Integrated application of transmission principle and electromagnetism principle of mechanical and electrical integration of electromagnetic actuator are analyzed in the output torque of the worm, the agency’s output torque expression is deduced, and the influence factors of the output torque is analyzed. Study results show that the output of the torque by the institutions of the permanent magnetic wheel transmission ratio, magnetic pole logarithm, center distance, torus radius of meshing point position Angle of worm, worm wheel, center distance and the ratio of the worm wheel radius, the air gap between the two interaction of magnetic wheels, the influence of such factors in the practical engineering design should consider when multiple influence factors, select reasonable parameters design.

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