Torque Calculation and Analysis of Permanent-Magnetic Gears

Yang Zhiyi, Zhao Han
School of Mechanical and Automotive Engineering,
Hefei University of Technology

Abstract

Permanent-magnetic gears are magneto-mechanical devices that are widely used to replace the ordinary mechanical gears and to transmit torque without any mechanical contact. The transmitted torque is one of the most important properties of magnetic gears. The torque characteristics of radial type permanent magnetic gears are investigated using ANSYS Program. The Maxwell stress tensor technique is used to calculate the torque of the magnetic gears. The results show that the transmitted torque of permanent magnetic gears is sensitive to the factors including the number of magnetic poles, the dimensions of the magnets, the air gap between two gears, the thickness of the yoke, transmission ratio, and the relative angular offset of the two gears. The obtained results can be used as a scientific basis for the design, optimization and application of permanent-magnetic gears.

Introduction

Permanent-magnetic gears are magneto-mechanical devices that utilize magnetic force and have some advantages such as structure, non-contact transmission, no friction and wear, no noise, without lubrication, dust-proof and water-proof, and so on. The new devices have broad application prospects in the field of robots, medical instruments, chemical engineering, food industry, and so on. However, complicacy of magnetic features causes difficulties in the design, analysis, and application of them. There are several methods for calculations of magnetic features, and Finite Element Method (FEM) is used most widely among them. ANSYS software is a large-scale, universal finite element program. It can be used to solve all complicate magnetic field problems. The gear transmissions are used to transmit torque, so the transmitted torque is one of the most important properties of magnetic gears (Yao, et al, 1997a, 1997b). In this paper, the magnetic field analysis of radial type permanent magnetic gears is investigated using ANSYS Program. And the Maxwell stress tensor technique is used to calculate the torque of the magnetic gears. At the same time, the torque characteristics are analyzed and discussed.

Transmission Types and Structures of Magnetic Gears

Similar to the normal gear transmission, the permanent magnetic gear transmission has three main types: the external gear transmission, the internal gear transmission and the pinion-rack transmission (Zhao and Tian, 2000). For example, Fig.1 illustrates an external gear transmission formed by a pair of cylindrical sintered NdFeB magnets, which are magnetized with 8-4 poles along the radial direction. The magnetic pole number of each cylindrical magnet is even. Circumferential length of each magnetic pole is equal. These make the driver can perform the given train ratio with the help of magnetic force. The two separated radial polarized cylindrical magnets constrain to rotate about their respective axes. The permanent magnetic gears are magnetically coupled to one another, and when the primary driver rotates, it imparts a torque to the follower and causes it to rotate. Fig.2 is a photo of the magnetic figure of the transmission that is created by using irons. The figure looks like a pair of the normal gears, but actually the teeth do not exist.

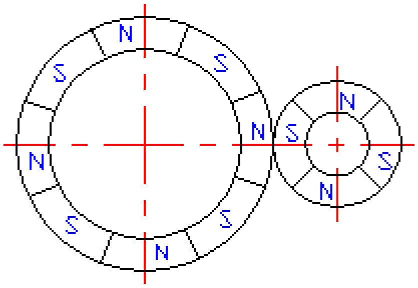

Figure 1 - The external magnet gear transmission

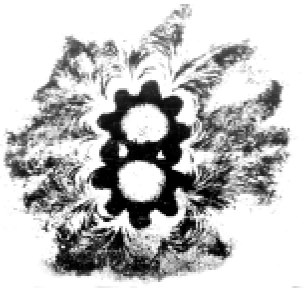

Figure 2 - The magnetic figure of external magnet gear transmission

Fig.3 illustrates the internal gear transmission. The large gear must be a ring body. Fig.4 is the rack and pinion transmission. The rack is a strip magnet with given poles distributed in one direction. The magnet gears can also be used to connect nonparallel, non-intersecting shafts at any angle to one another, but the angle is normally smaller than 45°.

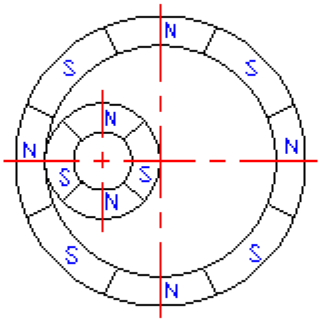

Figure 3 - The internal magnet gear transmission

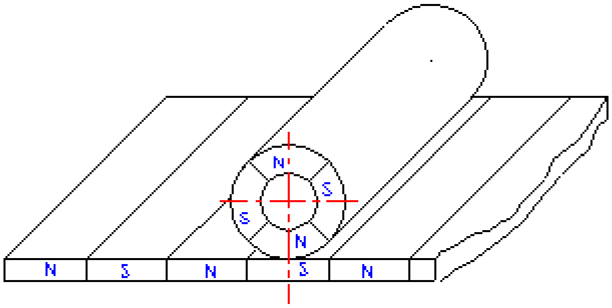

Figure 4 - The magnet rack and pinion transmission

Finite Element Analysis

As one of the most efficient numerical methods, FEM is routinely employed for the analysis of magnetic field recently (Sheng, 1991). In this section we introduce the magnetic field computation of permanent magnetic gears by using FEM. The Maxwell stress tensor technique is used to calculate the transmitted torque of the magnetic gears.

Magnetic field computation

It is well known that the permanent magnet with magnetization **M** is represented as a distribution of equivalent volume and surface current densities

$$\mathbf{J}_m = \nabla \times \mathbf{M} \text{ and } \mathbf{K}_m = \mathbf{M} \times \mathbf{n} \qquad (1)$$

respectively. The unit normal vector **n** is perpendicular to the surface of the permanent magnet. Supposing that the magnetization profiles of cylindrical magnets are uniform when going throughout the magnets, the $\mathbf{J}_m$ becomes zero.

The magnetic field caused by permanent magnetic gears is a kind of quasi-static magnetic field. According to the theory of the magnetic field, in the 2-D or 3-D magnetostatic approximation, the magnetic vector potential **A** satisfies the following equation:

$$\nabla^2 \mathbf{A} = -\mu \mathbf{J} \qquad (2)$$

where, μ is the magnetic permeability of the permanent magnets. **J** is the current density.

If the axial length of the magnetic gear is far greater than the dimensions in the cross-section plane, the magnetic field is assumed to be the 2-D field. In the equation (2), **A** and **J** are substituted by the component in **z** or axial direction, respectively.

In order to solve equation (2), the boundary conditions of the magnetic gears have to be known, the magnetic flux penetrates outside the permanent magnets. So we must built model for bigger air region around the magnetic gears. And the far field elements are employed on the boundary of model, thus the magnetic vector potential at the boundary of the model is zero. The second-order isoparametric elements are used in the internal region of the model. In this work, the variation principle is used in the discretization of the field equation (2). High order nonlinear equations are derived, and the Newton-Raphson iteration method is used for solving the nonlinear equations. The vector potential **A** and flux density **B** is calculated from the nodal values

$$\begin{cases} \mathbf{A} = \sum_e N_e \mathbf{A}_e \\ \mathbf{B} = \nabla \times \mathbf{A} \end{cases} \qquad (3)$$

where, N_e is the element shape function, $\mathbf{A}_e$ is the nodal magnetic vector potential. Thereby the magnetic field distribution of permanent magnetic gears can be obtained.

Fig.5 shows the element mesh of one pole of the magnetic gear. Fig.6 shows the magnetic field distribution of the external magnet gear transmission. Each magnet is magnetized with 8-8 poles along the radial direction, the relative angular offset α=22.5°.

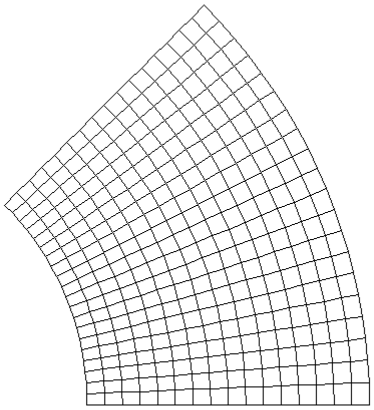

Figure 5 - The mesh of a pole of the magnetic gear

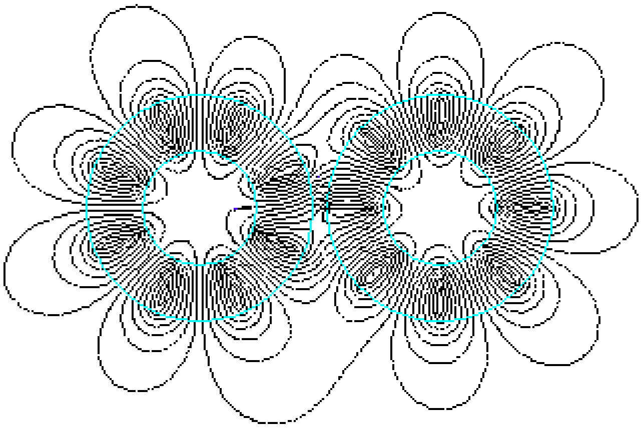

Figure 6 - The magnetic field distribution of the external magnet gear transmission

Calculation of torque

A method based on Maxwell's stress tensor is commonly used in the calculation of forces and torques in the finite element analysis of electric devices. For the 2-D application, this method uses extrapolated field values and results in the following numerically integrated surface integral

$$\mathbf{F} = \oint_S \boldsymbol{\sigma} \cdot dS \qquad (4)$$

where $\boldsymbol{\sigma}$ is Maxwell's stress tensor and S is the integration surface.

For a 2-D analysis, the corresponding electromagnetic torque about +z axis is given by

$$\mathbf{T} = \mathbf{Z} \cdot \frac{1}{\mu_0} \int_S \mathbf{r} \times \left[(\mathbf{n} \cdot \mathbf{B})\mathbf{B} - \frac{1}{2}\mathbf{B}^2\mathbf{n} \right] dS \qquad (5)$$

where **Z** is the unit vector along +z axis, **r** and **n** are the position vector and the unit surface normal vector in the global Cartesian coordinate system, respectively.

3-D application is an extension of the 2-D case, and the expression of the torque can be derived easily.

Torque Characteristics Analysis

The transmitted torque is a function of several variables, including the number of magnetic pole pairs, the dimensions of the magnets, the air gap between two gears, the thickness of the yoke, transmission ratio, and the relative angular offset of the two gears, and so on.

In order to analyze the magnetic field and calculate the torque, the geometry and materials used should be accurately represented in the model. The relative permeability of NdFeB permanent magnet is 1 in all directions and its coercive force is 830 kA/m in the magnetized direction. The relative permeability of air is 1 in all directions. The iron for the inner ring of magnetic gear is represented by its non-linear B-H characteristics. The torque is computed on the driven gear.

Influence of the relative angular offset and the air gap between two gears

The torque of the magnetic gears depends on the relative angular offset of one gear to the other. The relative angular offset, α, is defined from the center of the north pole on one gear to the center of the south pole on the other (as shown in Fig.1, α=0°). Fig.7 shows the torque of the radial magnetic gears as a function of the relative angular offset and the air gap between two gears (d=1, 2, 3 mm, respectively) for cylindrical magnets. The outer and inner radii are 8 mm and 4 mm, respectively. The axial length of magnets is 16 mm. There are 8 poles on each magnetic gear.

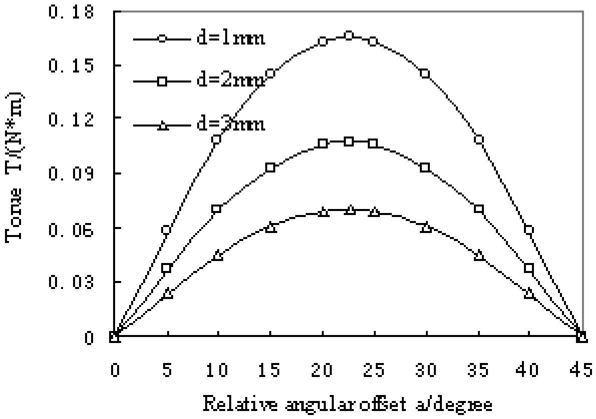

Figure 7 - The torque versus the relative angular offset and the air gap

When α is equal to zero, the adjacent magnets on the separate gear are face to face with the same magnetizations. The torque is equal to zero. This position is stable. When the driver gear begins to rotate, the driven gear will have a relative angular offset. The transmitted torque is increased as the relative angular offset is increased. When the relative angular offset is half a pole pitch, the torque value is the maximum. After the pullout, the transmitted torque is decreased as the relative angular offset is increased. When α equals a pole pitch, the torque value is also zero, but as the adjacent magnets on the separate gear are face to face with opposite magnetizations, this position is unstable. The curves in Fig.7 also show that the torque transmitted by two gears with fixed number of pole pairs is decreased quickly as the air gap between two gears is increased. In fact, for a given number of pole pairs, the level of the magnetic induction rapidly decreases with the air gap increasing.

Influence of the geometry dimension and the number of pole pairs

Fig.8 shows the maximum torque of the magnetic gears as a function of the number of pole pairs and the geometry dimension without any iron yoke for a given air gap of 2 mm. For a given number of pole pairs, *p*, the maximum torque is obtained for a relative angular offset of π / *p*.

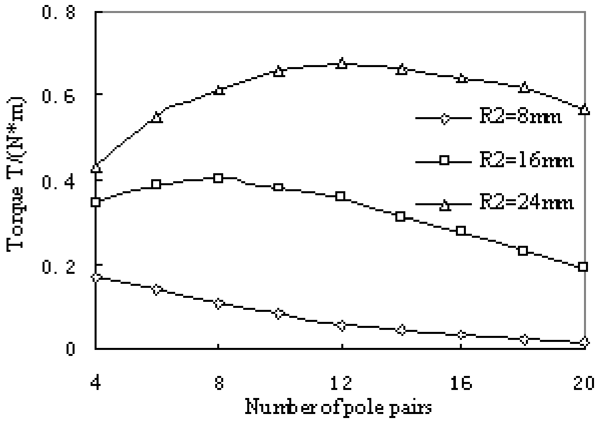

Figure 8 - The torque versus the number of pole pairs and the geometry dimension

This analysis explains the size effect of the radius of cylindrical magnets. From these curves, we observed that the peak is shifted from 4 poles to 8 poles, and to 12 poles with increasing the outer radius of the magnets from 8 mm to 16 mm, and to 24 mm, respectively. The radial width of magnets and the axial length of the above cylindrical magnets are fixed to 4 mm and 16 mm, respectively. This can be understood by considering the magnetic field strength on the surface and the area of each pole, the magnetic field strength is gradually increased with the number of the poles, and however the area of the surface of each pole is decreased as increasing the number of the poles. Therefore the combination of the two effects results in a maximum peak and also this maximum peak should shift to the larger number of poles with larger radius of the cylindrical magnets. So the torque value reaches a maximum corresponding to an optimal width of the magnets.

Influence of the transmission ratio

Similar to the normal mechanical gears, the variable transmission ratio of the permanent magnetic gears can be acquired. Under the conditions that the number of pole pairs and outer radius of the driver gear are fixed to given values, the number of pole pairs and outer radius of the driven gear will be increased as increasing the transmission ratio. Otherwise, the stable rotate speed ratio of the two gears could not be achieved. Fig.9 shows the maximum torque of two magnetic gears (with the air gap d=2 mm, and without any yoke) as a function of transmission ratio for a given driver gear. We can observe that the maximum torque is increased linearly as increasing the transmission ratio.

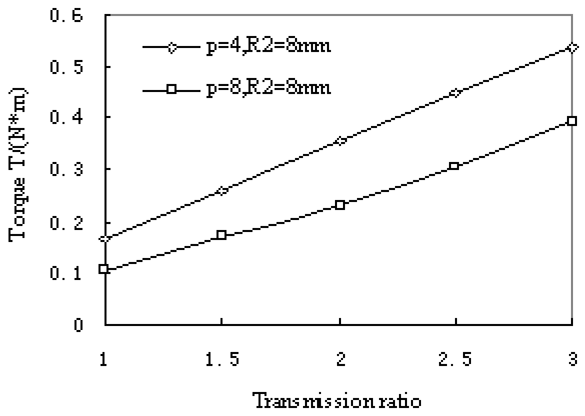

Figure 9 - The torque versus the transmission ratio

Influence of the thickness of iron yoke

As for the influence of the thickness of iron yoke, the enhancement of the torque is dependent on the thickness of the yoke. Fig.10 shows the maximum torque of magnetic gears of out radius 32 mm as a function of the number of poles, with its yoke thickness varied from 0 to 10 mm. The radial width and axial length of magnets and the air gap are fixed to 4 mm, 32 mm and 2 mm, respectively. It is clear that the torque is enhanced by the existence of an iron yoke, and its value as a function of the number of pole is saturated for iron yoke with thickness above 1 mm. From these curves, we observed that the peak is shifted from 10-pole for the case without any iron yoke to 12-pole for the case with a iron yoke of above 1 mm.

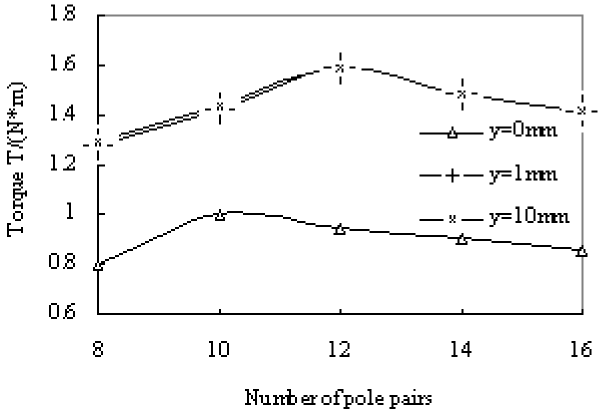

Figure 10 - The torque versus the number of pole pairs for different thickness of iron yoke

Conclusion

In this paper, the magnetic field analysis of radial type permanent magnetic gears is investigated using ANSYS Program. And the Maxwell stress tensor technique is used to calculate the torque of the magnetic gears. Then the torque characteristics are analyzed and discussed. The results show that the transmitted torque of permanent magnetic gears is sensitive to the factors including the number of magnetic poles, the dimensions of the magnets, the air gap between two gears, the thickness of the yoke, transmission ratio, and the relative angular offset of the two gears.

These results can be used as principles of design and optimization for the permanent magnetic gears. The optimal design of magnetic gears will be done using 2D or 3D FEM. However, compared to other optimal methods, the optimal design process using FEM may be cost more calculation time because each iteration calculation is a solving process of FEM. In addition, the final dimensions of the magnetic gears should be modified by experimental data. The optimal design using 2D or 3D FEM and related experiment of permanent magnetic gears will be our future work.

References

1) Sheng, J.N., 1991, “Numerical Analysis of Engineering Electromagnetic Field,” Xi’an Jiaotong University Press, Xi’an, China.

2) Yao, Y.D., Huang, D.R., Hsieh, C.C., et al., 1997a, “Simulation Study of the Magnetic Coupling between Radial Magnetic Gears,” IEEE Transactions on Magnetics, Vol. 33, No. 2, pp. 2203~2206.

3) Yao, Y.D., Huang, D.R., Lee, C.M., et al., 1997b, “Magnetic Coupling between Radial Magnetic Gears,” IEEE Transactions on Magnetics, Vol. 33, No. 5, pp. 4236~4238.

4) Zhao, H., and Tian, J., 2000, “Design of Rare-Earth Magnetic Gear Transmission with FEM,” Mechanical Science and Technology, Vol. 19, No. 2, pp. 207~209.