Design and Characteristic Analysis of Non-Contact Magnet Gear for Conveyor by Using Permanent Magnet

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Abstract—**This paper deals with the design of the non-contact magnet gear for conveyors. The magnet gear, consists of two permanent magnets with skew, is a device for changing the transmission for direction without the mechanical contact between two magnets. To perform a parametric study, the important design variables related to the permanent magnet are selected, and then the influence of the design parameters on the magnetic torque performances is investigated. The 3-dimentional electromagnetic Finite Element Method (FEM) is used for the characteristic analysis. Based on these results, the magnet gear is designed and verified by comparing the analysis result with the experimental data.**

Keywords— desingn parameter; FEM; magnet gear; magnetic torque; skew; permanet mangent

I. Introduction

Factory automation systems for the equipment of semiconductor manufacturing, LCD and PDP have to maintain the high clean class. The conventional conveyor of these systems adopts belts and various mechanical gears for power transfer from a drive source, hence dust is raised due to the contact manner. Therefore, some special cleaning mechanisms are needed to reduce the dust. Recently, permanent magnets, owing to the development of various high-grade magnetic materials, are widely used in many applications such as motors, sensors, actuators, PM torquers, etc. [1]. The magnet gears using permanent magnets are an attractive transmission mechanism for the conveyor system because they do not generate any dust.

The non-contact magnet gear consists of the driven and driving permanent magnet with skew, like the helical type gear shape. As shown in Fig. 1, the respective axes of the upper magnet and the lower magnet intersect each other perpendicularly and the respective peripheral surfaces are close to each other, but not in contact with each other, separated by a relatively small airgap. The torque is produced by the electromagnetic phenomenon between two permanent magnets. The permanent magnet with skew mounted at a 90-degree angle change the transmission for direction without any direct contact. Therefore, the magnet gear is very useful for the conveyor because of: (i) preventing dust particles and mechanical wear, (ii) suppressing the generation of noise, (iii) saving the cost, (iv) having the superior reliability and long service life, compared to a class of conventional gears with contact drive.

It is necessary to know exactly on which the parameters has an effect in order to design the demands on the magnet gear. Its characteristics are achieved by a numerical analysis considering the electromagnetic field distribution in 3-dimensional. Therefore, this paper presents the design criteria of the non-contact magnet gear. The influence of design parameters on its characteristics is investigated. To study the parametric analysis, the follow parameters are chosen: the skew angle, magnetizing distribution, number of pole, thickness of magnetizing direction, overhang length and so on. These design variables are concerned with permanent magnet shapes and its dimensions. The optimal dimension to reduce the magnet volume, that means the reduction of cost, is selected from the parametric study. The electromagnetic field is analyzed by three-dimensional FEM and then the Maxwell stress tensor is used for calculating the magnetic torque, where the motion and skew configuration of the magnet gear are taken into account for the field and force computation in the three-dimensional space.

First, the validity of available analysis program with FEM is achieved by comparing with experimental values of a sample magnet gear. Secondly, the performance and characteristic of the magnet gear for variations of design variables is investigated. From the results, the magnet gear with torque requirements is designed for the conveyor. The magnetic torque of the designed model is compared with the measured data.

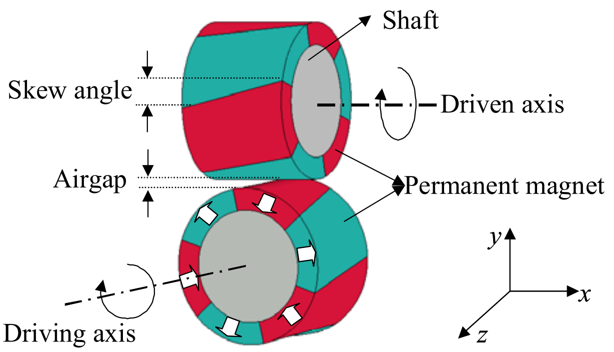


Fig. 1 Configuration of magnet gear composed of two permanent magnents with skew (upper: running gear, lower: passive gear)

II. Design Model and Analysis Method

A. Design Model

Fig. 1 describes the relative position of each magnet in the magnet gear. The analysis model has two permanent magnets with skew that is the driving and driven permanent magnet, respectively. The each permanent magnet is fixed on two shafts cross at right angle. The magnet gear has a space between two permanent magnets for the non-contact drive. The function of upper permanent magnet is to the running gear and the lower is to the passive gear. With the help of the skew in the permanent magnet, the driven magnet can be smoothly rotated according to the rotation of the driving magnet.

Their magnetic material is a ring type Nd-bonded magnet. The Nd-bonded magnet is mainly ferrite powder and rare earth compound such as Nd-Fe-B. Its manufacturing cost is lower than that of Nd-sintered magnet. The Nd-bonded magnet with residual flux density of approximately 0.7(T) is used to design the magnet gear.

B. Operating Charteristics of PermanentMagnet

The permanent magnet is useful for the magnet gear because it stores magnetic energy, and this energy is not consumed in the device operation. When operating within normal limits, the magnet retains its energy for an indefinite period. Permanent magnets are hard magnetic materials characterized by large hysteresis loops, as shown in Fig. 2. The second quadrant is known as the normal demagnetization curve that represents inherent property of permanent magnets. This slope is the recoil permeability. The line from the origin through the open-circuit operating point is called the load line. The slope is the permeance coefficient. This depends on dimensions, magnetic properties used as magnetic circuits for the flux path driven by the permanent magnet. The magnet permeance p_c is given by [2]

$$p_c = \frac{\sigma}{f}\frac{A_m}{A_g}\frac{l_m}{l_g} \tag{1}$$

where σ is the leakage coefficient, f is the Mageto-Motive Force(MMF) drop coefficient. A_m and A_g is the pole area in permanent magnet and airgap, respectively. l_m is the thickness

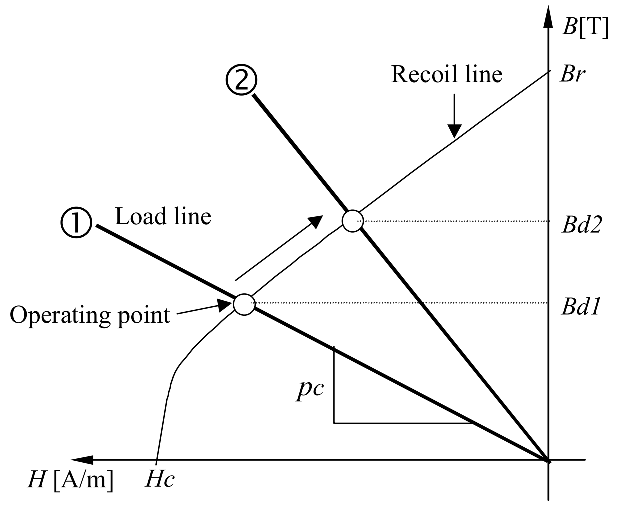


Fig. 2 B/H characteristic of a hard permanent magnet material. This is the second quadrant part of the full hysteresis loop. Also shown is the normal operating point, the load line.

of magnetizing direction and l_g is the airgap. The operating point, means the available flux in the magnet, is determined by the recoil line and the load line. When the temperature is increased, some degradation of magnetic properties occurs. The reversible changes in remanence is usually quoted in percent per Kelvin; described by temperature coefficients. Its average value in Nd-Fe-B magnets is –0.13(%/K), which is the smallest in permanent magnet materials. And the permanent magnets made of Nd-Fe-B materials have a high residual flux density. Thus, This permanent magnet is very useful for the magnet gear.

In the magnet gear, the shafts are inserted into the hole of two permanent magnets. The materials used in the shaft effect on the performance of the permanent magnet. The permeability of the stainless steel for the shaft is equal to that of air. So, the shaft with a soft magnetic material, such as cast iron and cast steel, is can be used to increase the operating point. The magnet's operating point moves up the straight part of the characteristic from point 1 to point 2, shown in Fig 2. Therefore, the magnetic torque increases by increasing the flux.

C. Analysis Method

The magnet gears have three-dimensional flux distributions because of their relative position and skew so that the three-dimensional analysis is needed based on numerical analysis methods. For the electromagnetic field analysis, three-dimensional FEM is used to solve the three-dimensional shaped model. The electromagnetic governing equation on quasi-static field problems with magnetic scalar variables can be obtained by Maxwell's electromagnetic equation. The governing equation with magnetic scalar potential Ω can be expressed as follows [3]:

$$\nabla \cdot (\mu \nabla \Omega) = 0 \tag{2}$$

where, μ is the magnetic permeability.

Using the magnetic scalar potential in the three-dimensional analysis is more useful because it has only one unknown variable at each node. However, the magnetic vector potential has three degrees of freedom at each node. It takes a lot of time to solve a large matrix size than that of that magnetic scalar potential.

The Maxwell stress tensor method from the magnetic field analysis is used to calculate the magnetic torque. The torque is obtained by the surface integration of a stress tensor vector $\boldsymbol{P}$ over an air gap enclosing the magnet surface as follows [4]:

$$\boldsymbol{T} = \oint_s \boldsymbol{r} \times \boldsymbol{P} \, d\boldsymbol{S} \tag{3}$$

where, $\boldsymbol{r}$ is the distance vector of a point to axis rotation. Maxwell's stress tensor can be written as:

$$\boldsymbol{P} = \frac{1}{\mu_0}(\boldsymbol{n} \cdot \boldsymbol{B})\,\boldsymbol{B} - \frac{1}{2\mu_0} B^2 \boldsymbol{n} \tag{4}$$

where, μ_0 is the permeability of free space, $\boldsymbol{n}$ is the direction of the normal unit vector on the surface, $\boldsymbol{B}$ is the flux density solved by electromagnetic FEM.

III. Design and Analysis Results

A. Analysis of Sample Model

The sample magnet gear is used for the verification of the analysis method. Fig. 3 shows the generated mesh for only one magnet. The hole is filled with air. For the magnetic field analysis, the element is a tetrahedron having four nodes. In modeling the skewed permanent magnet, the analysis model is composed of several non-skew models cut by planes perpendicular to the shaft. The residual flux density of the permanent magnet with six poles is 0.62(T) and the skew angle is 45(deg.). The magnetizing direction is a fixed direction.

In Fig. 4, 5 and 6, the spatial flux density distribution of the skewed model on the surface of the permanent is compared with that of the non-skew model. In case of the skewed model, the normal component B_n has the square-wave distribution and the lateral leakage fluxes, tangential component B_t, exist in both ends of the permanent. On the other hand, the normal component of the non-skewed model is a sine-wave distribution and the lateral flux leakage along z-direction is larger than that of the skewed model, which is due to the effect of skew. In Fig. 5, the B_θ component between poles caused by the skew is more increased. The magnetic flux distribution vector of the skewed and the non-skewed model is plotted on Fig. 7.

Fig. 8 shows the measured and calculated flux density along the surface in the middle of permanent magnet length. To measure accurate the flux density, a soft magnet material encircles the permanent magnet. The airgap between magnetic material and permanent magnet is 2.0(mm). The analysis result is similar to the measurement.

Furthermore, to examine the validity of the analysis method, the magnetic torque of the magnet gear is calculated. Fig. 9 shows the mesh generation and flux density distribution of the sample magnet gear. The number of element is 229070 in the analysis region for the electromagnetic field analysis.

Fig. 10 presents that the variation of magnetic torque varying with rotation angle of the permanent magnet. The calculated torque at the maximum torque point is a good agreement with the measured one. In this way, the calculation programs used in this study are suitable to design the magnet gear.

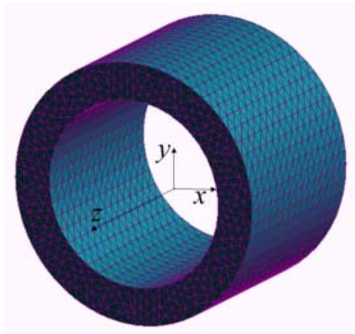


Fig. 3 Generated mesh of analysis model

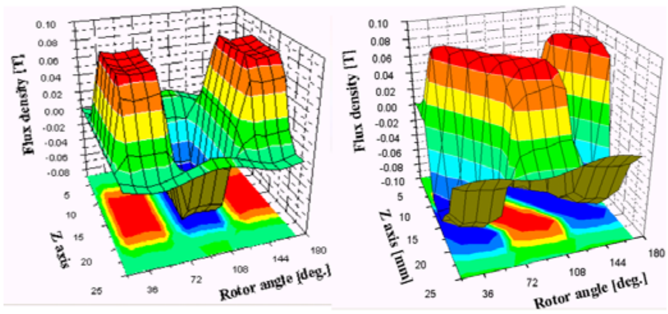


Fig. 4 Flux density distribution of normal component B_n at the surface of permanent magnent (Left: Nonskewed model, Right: Skewed model)

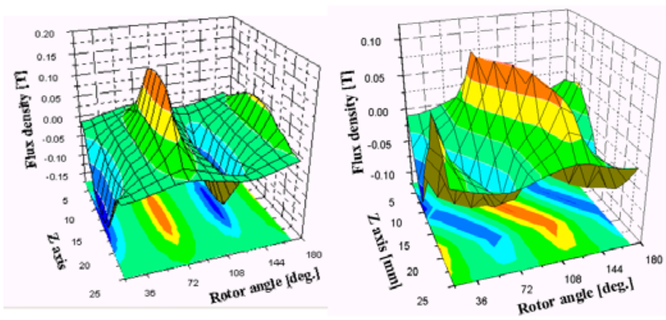


Fig. 5 Flux density distribution of tangential component B_t at the surface of permanent magnent (Left: Nonskewed model, Right: Skewed model)

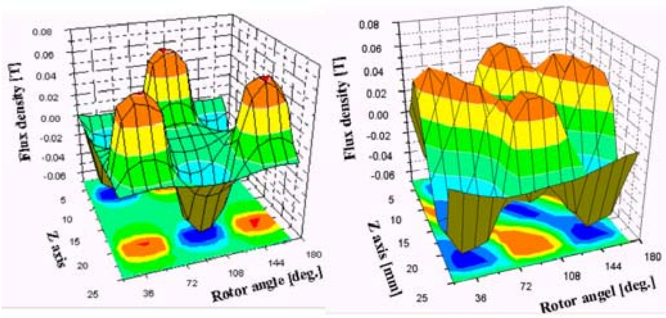
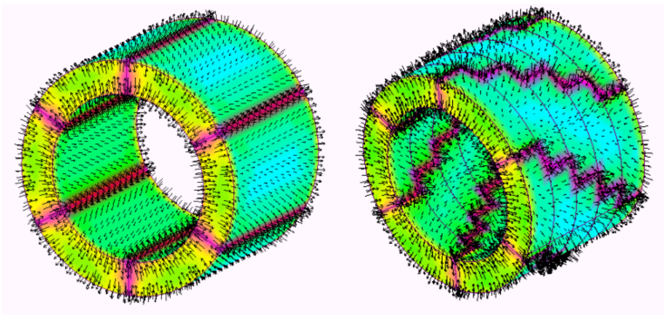


Fig. 6 Flux density distribution of z component B_z at the surface of permanent magnent (Left: Nonskewed model, Right: Skewed model)



(a) (b)

Fig. 7 Flux distribution arrow plot
(Left: nonskewed model, Right : skewed model)

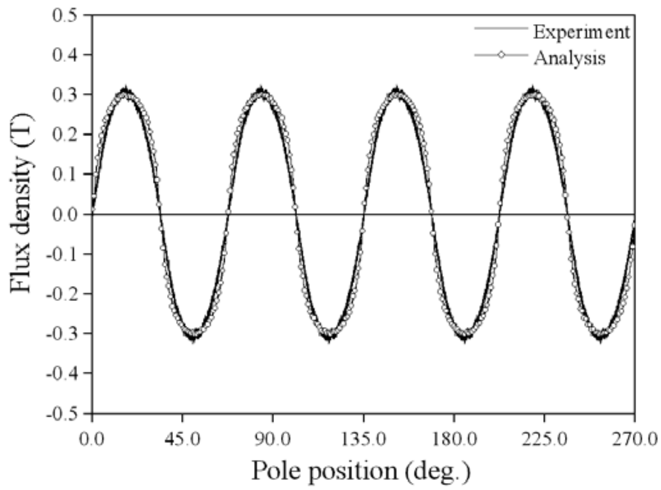


Fig. 8 Experiment and calculated flux density in airgap when the permanent magnent is encicled by a soft magnetic material

B. Parametric Study

The initial dimension as shown in Table I is determined for the parametric study. Based on the initial dimension, the parametric analysis is performed to design the magnet gear. The airgap between the driven and the driving permanent magnet is 0.5(mm). The Nd-bonded magnet of 0.7(T) is used. It is assumed that the magnetizing direction of the permanent magnet is a fixed direction. This assumption results from anisotropic properties of Nd-bonded material.

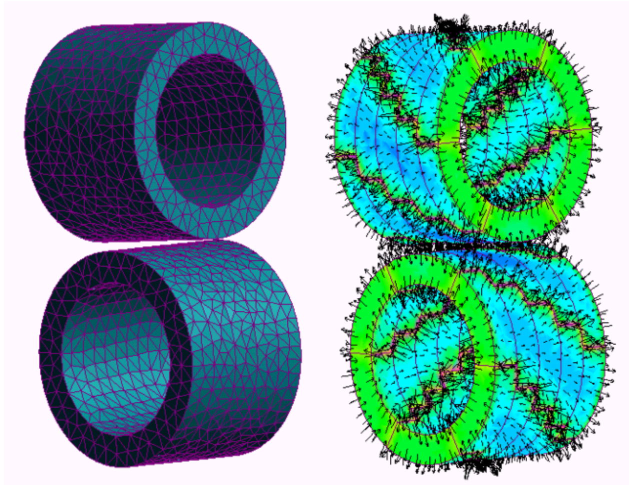


Fig. 9 Mesh generation and flux distribution arrow plot

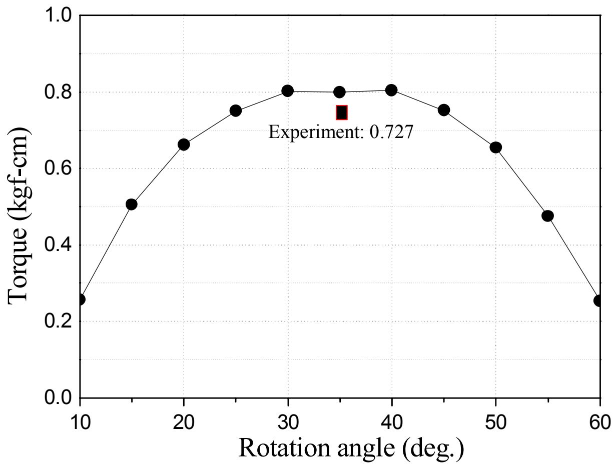


Fig. 10 Comparison of measurement and analysis result of magnetic torque with roatation angle

TABLE I. INITIAL DIMENSION OF PERMANENT MAGNET FOR PARAMETRIC STUDY

Inner diameter	***Outer diameter***	***Length***	***Pole number***
30.0 (mm)	24.0 (mm)	24.0 (mm)	6

Fig 11 shows the maximum value, in the magnetic torque as a function of rotation angle, for the skew angle. The number of pole in the analysis model is six. The torque increases until mechanical skew angle 45(deg.) and decreases after passing by that angle because the flux linkage decreases. The permanent magnet with the skew angle of 45(deg.) allows the magnet gear to produce a large magnetic torque.

The pole number in design parameters has influence on the magnetic torque. The maximum magnetic torque versus the number of poles is shown in Fig. 12 when the skew angle is 45(deg.). The maximum toque has the peak value at the 8-pole, followed by a fall. This observation leads to a conclusion that the 8-pole is the most suitable for increasing the magnetic torque.

To analyze overhang effects, the length of two magnets used in the magnet gear is different. The length of the upper magnet is larger than that of the lower magnet. The skew angle and the pole number are 45(deg.) and 6 poles, respectively. The length of the driving permanent magnet is 24(mm) and that of the driven permanent magnet is changed from 24(mm) to 40(mm). In Fig. 13, the torque performance slightly increases by increasing the length of the driven magnet. The magnetic torque over the length of 32(mm) is almost constant value and the torque per unit cost is decreased.

Fig. 14 shows the variation of maximum torque for the thickness of magnetizing direction. The inner and outer diameter is changed as shown in Table on Fig. 11. The skew angle and the pole number are 45(deg.) and 6 poles, respectively. The maximum torque steadily increases with an increase in the thickness of magnetizing direction. This is due to the increase of effective flux driven by the permanent magnet. And prices go up because the volume of permanent magnet is increased in proportion of the thickness of magnetizing direction.

Fig. 15 shows the maximum torque varying with the outer diameter of the permanent magnet when the thickness of magnetizing direction is not changed as 3.0(mm). The inner and outer diameter is changed as shown in Table on Fig. 11. The magnetic torque remains constant at the whole range because the flux driven by the permanent magnet is almost constant. The change of the outer diameter has not influence on the magnetic torque due to the constant thickness of magnetizing direction. The volume of permanent magnet is increased in proportion of the outer diameter. Thus, the torque performance per unit cost is smaller than that of the other parameters.

Fig. 16 presents the comparison of the magnetic torque characteristics in the case of the shaft of magnet gear filled with the soft magnetic material and the shaft filled with the nonmagnetic material. The torque caused by the magnetic material shaft increases by 30(%) compared to that caused by the nonmagnetic material shaft. The operating point of the permanent magnet is increased. As a result, the magnetic gear with the soft magnetic material shaft generates a large magnetic torque than that with the nonmagnetic material shaft.

C. Final Design of Magnet Gear and Experiment

Based on the detailed investigation, the magnet gear is designed for the conveyor system that needs the magnetic torque of 3.5(kgf.cm). The magnet volume within a given design space considering the system is minimized to reduce the cost of permanent magnet. The final configuration and dimension is illustrated in Fig. 17. The designed permanent magnet has eight poles and skew angle of 45(deg.).

Fig. 18 shows the experiment unit constituted by load cell, two permanent magnets and indicator to measure the magnet gear performance. The indicator displays the magnetic toque value. The measured torque is 3.64(kgf-cm) when the shaft is the stainless steel that agrees with the calculated value.

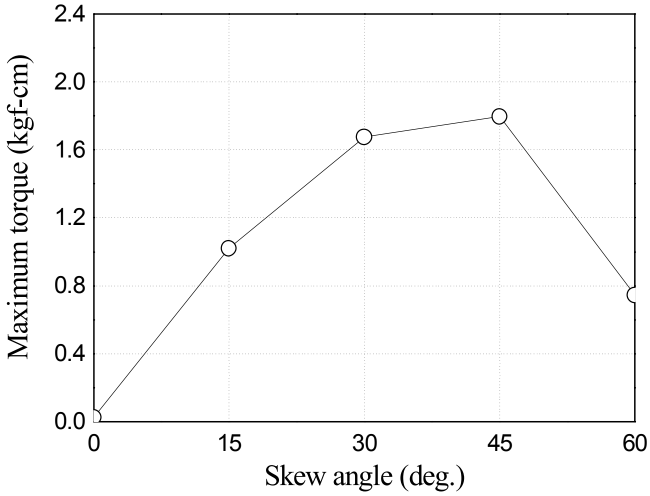


Fig. 11 Maximum magnetic torque vs. skew angle at six pole

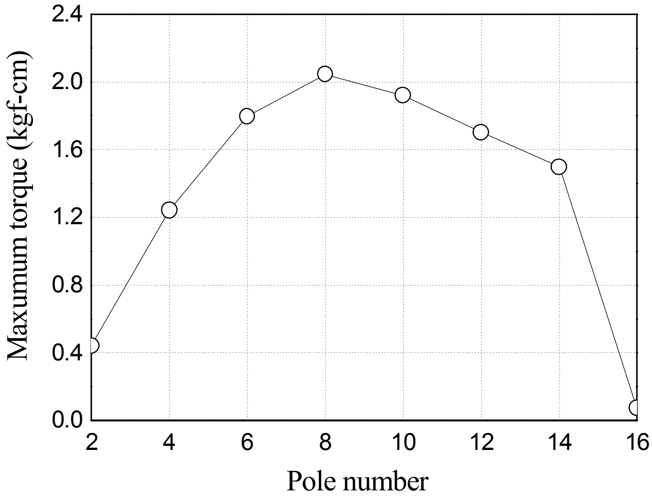


Fig. 12 Maximum magnetic torque vs. the number of pole at six pole with skew angle 45(deg.)

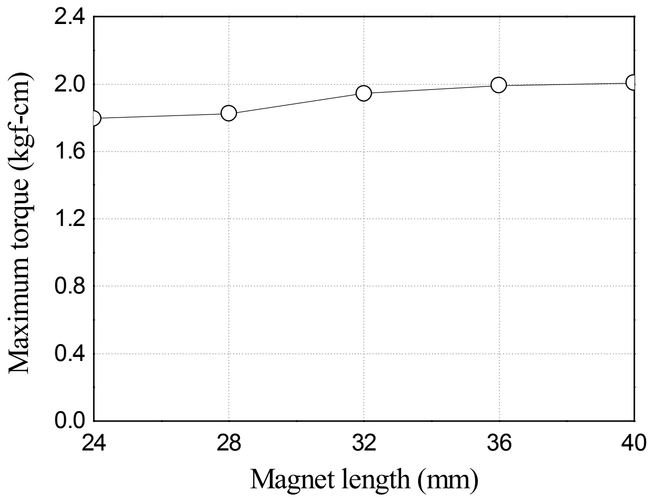
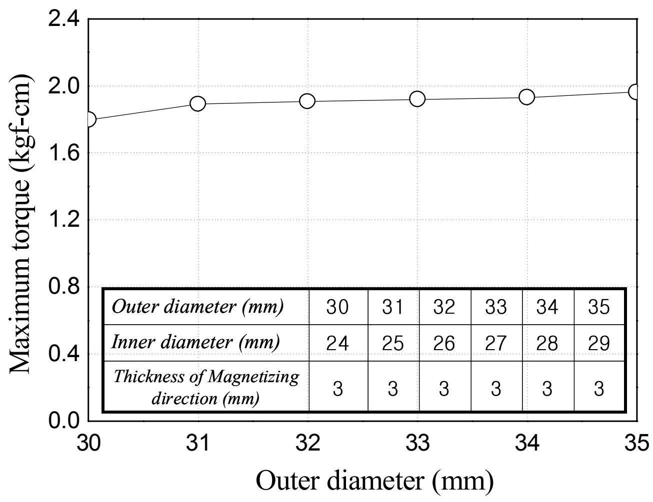
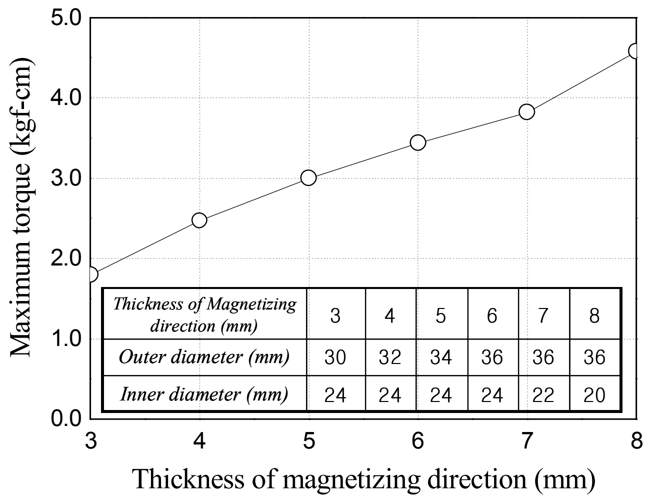


Fig. 13 Maximum magnetic torque for the length of permanent magnet at six pole with skew angle 45(deg.)



Outer diameter (mm)	30	31	32	33	34	35
Inner diameter (mm)	24	25	26	27	28	29
Thickness of Magnetizing direction (mm)	3	3	3	3	3	3

Fig. 14 Maximum magnetic torque according to outer diameter at six pole with skew angle 45(deg.) when the thickness of manetizing direction is constant as 3.0(mm)



Thickness of Magnetizing direction (mm)	3	4	5	6	7	8
Outer diameter (mm)	30	32	34	36	36	36
Inner diameter (mm)	24	24	24	24	22	20

Fig. 15 Variaton of maximum magnetic torque for the thickness of magnetizing direction at six pole with skew angle 45(deg.)

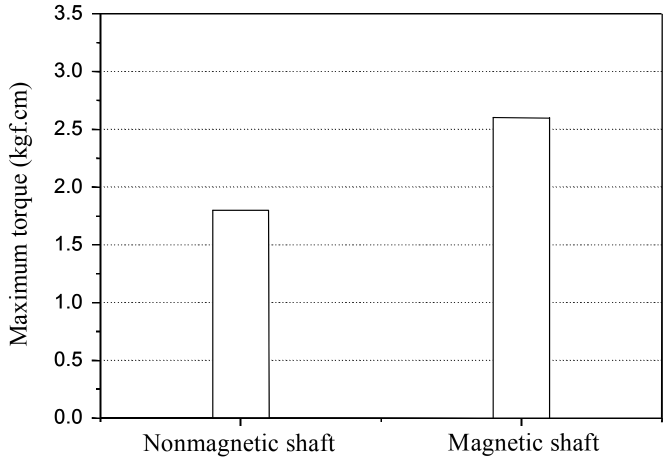


Fig. 16 Maximum magnetic torque vs. magnetic material of shaft at six pole with 45(deg.) skew angle

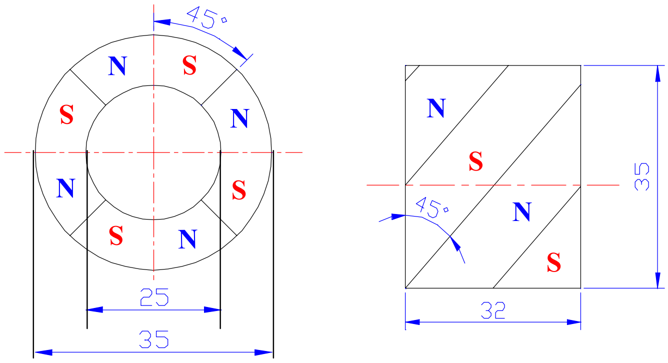


Fig. 17 Confuguration and dimension of final model (Left: front view, Right: side view)

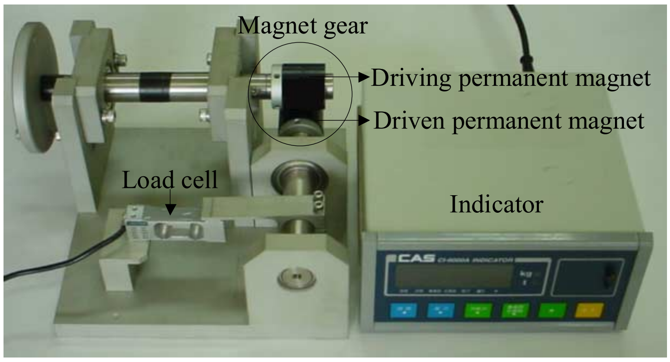


Fig. 18 Experiment unit to measure the magnetic torque of magnet gear

IV. CONCLUSION

This work studies the effect of parameter changes on the magnetic torque of the magnetic gear. The detailed trends of the performance according to various design parameters are investigated by three-dimensional electromagnetic FEM proved by the comparison of the experimental result. From the results, the final permanent magnet dimension considering the manufacturing cost and the torque performance is determined. This investigation can be effectively used for the non-contact magnet gear design for conveyor systems.

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