Magnetic Gearing System

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Abstract

With the advent of magnetic gears, researchers have developed a new breed of permanent-magnet machines. These magnetic-gearered permanent-magnet machines artfully incorporate the concept of magnetic gearing into the permanent-magnet machines, leading to low-speed high-torque direct-drive operation. Gears and gearboxes are extensively used for speed change and torque transmission in various industrial applications. It is well known that the mechanical gear has a high torque density, but suffers from some inherent problems such as contact friction, noise, heat, vibration and reliability are of great concern. In order to avoid these types of problems we are using magnetic meshing gears. That is the gears are meshed together with the help of magnetic force of attraction without making into contact. By using such kind of gearing systems we can reduce the wear and tear that are commonly seen in mechanical spur gear systems and the magnetic gears works smoothly without any sound and the main advantage of magnetic gearing is it will not get heated as long as it works. Magnetic gearing systems can be used in vehicle transmissions that reduce the friction and improve the efficiency without using any type of additional lubricants. We are using high power rare earth neodymium magnets for the purpose of making gears. Neodymium magnets are powerful magnets which are about 12 times stronger than normal magnets used in speakers.

Keywords: Transmission; Magnetic meshing; Torque density

I. INTRODUCTION

Gears and gearboxes are extensively used for speed change and torque transmission in various industrial applications. It is well known that the mechanical gear has a high torque density, but suffers from some inherent problems such as contact friction, noise, and heat, while vibration and reliability are of great concern. In contrast, the magnetic gear (MG) offers significant advantages of reduced acoustic noise, minimum vibration, free from maintenance, improved reliability, inherent overload protection, and physical isolation between the input and output shafts. However, for a long time, MGs have received relatively little attention, probably due to the poor torque density and relative complexity of the magnetic circuits.

The magnetic gear resembles in part, the traditional mechanical gear. All cogs of each gear component of magnetic gears act as a magnet with periodic alternation of opposite magnetic poles on mating surfaces. Gear components are mounted with a "cushioned" backlash capability similar to other mechanical gearings with no cushioning effect. Although they can exert as much force as a traditional gear, such gears work without touching and so are immune to wear of mating surfaces, have very low noise and can slip without damage making them very reliable. They can be used in configurations that are not possible for gears that must be physically touching and can operate with a barrier completely separating the driving force from the load. The magnetically coupled gear can transmit force into a hermetically sealed enclosure without using a radial shaft seal, which may leak. Hermetically sealed processes are not contaminated or chemically affected by the magnetic gear. This can be an advantage in explosive or otherwise hazardous environments where leaks constitute a real danger.

A magnetic gear uses permanent magnets to transmit torque between an input and output shaft without mechanical contact. Magnetic gears can achieve with efficiency greater than 99% at full load and with much higher part load efficiencies than a mechanical gear. For higher power ratings a magnetic gear will be smaller, lighter and lower cost than a mechanical gear. Depending on the space available a magnetic gear may be the only viable technology.
II. LITERATURE REVIEW

The idea of MGs can be tracked down to the beginning of the 20th century. In 1913, a US Patent Application described an electromagnetic gearing which should be the original topology, but almost no one was interested in it at that time. Until a MG topology quite similar to a mechanical spur gear was proposed by Faus in 1941, people gradually paid attention to MGs. However, low utilization and poor performance of ferrite permanent magnet (PM) material made it impossible to be widely used in industry. Until the high-performance neodymium iron born (NdFeB) PM material was invented in the 1980s, the research on MGs aroused great interests again. Naturally, the earlier MG topologies were converted from mechanical gear topologies. These converted MGs simply replaced the slots and teeth of iron core by N-poles and S-poles of PMs, respectively. The low utilization of PMs was the key problem which caused poor torque density.

In 2001, Atallah and Howe proposed a high-performance MG named as the coaxial magnetic gear (CMG), whose principle of operation was based on the modulation of the magnetic fields produced by two PM rotors via the ferromagnetic pole-pieces. Unlike the converted MGs, the CMG has a higher torque density, because all the PMs simultaneously contribute to torque transmission. Based on the field modulation principle, many improved CMG topologies are proposed to further obtain a better performance. In view of the coaxial structure, the CMG can be artfully integrated with a high speed outer-rotor PM brushless machine to constitute a composite electrical machine named as the magnetic-gear permanent-magnet (MGPM) machine, which can achieve low-speed high-torque driving while providing high torque density.

An analysis has been done by X. Li, K.T. Chau, M. Cheng1 and W. Hua1 [1] This paper deals with the comparison between magnetic gears and the mechanical gears.

And another study done by K. T. Chau1, Dong Zhang, J. Z. Jiang, Chunhua Liu1, and Yuejin Zhang [2] and it deals with novel in-wheel motor, which artfully integrates a magnetic gear into a permanent-magnet brushless (PMBL) DC motor so that they can share a common PM rotor, hence offering both high efficiency and high power density. Moreover, the low-speed requirement for direct driving and the high-speed requirement for compact motor design can be achieved simultaneously.

III. MATERIAL SPECIFICATIONS

A. Neodymium Magnets:

![Image of Neodymium Magnets]

Figure 1 shows Cubic shaped Neodymium magnets. Neodymium magnets are a member of the Rare Earth magnet family and are the most powerful permanent magnets in the world. They are also referred to as NdFeB magnets, or NIB, because they are composed mainly of Neodymium (Nd), Iron (Fe) and Boron (B). Neodymium magnets are over 10x stronger than the strongest ceramic magnets. Here we are using N52 grade high strength cubical shaped Neodymium magnets of size 30mm*20mm*10mm

B. Gear Blank:

The gear blank is made of hylam sheets. There are six gear blanks two having a diameter of 8 cm, two of 20 cm and a pair of 18 cm and 10 cm. The different diameters are chosen to obtain different gear ratios peripherally. The different gear ratios demonstrated are 5:4(20cm to 8cm dia), 9:5(18cm to 10cm dia) and 4:5(8cm to 20cm dia). The gear blanks have thickness of 30 mm. Slits of depth 10 mm are provided on each blank in order to place the permanent magnets. The magnets are fixed on each slit with the help of an adhesive. The distance between the central axis of two magnets was decided to be 37mm through experimentation to avoid slip and to get maximum output. The gap between two gear blanks was decided as 3mm for better results through experimentation.
Figure 2 shows the Magnetic gear blank made of hylam material and cubical shaped Neodymium magnets are placed inside the slots provided.

C. Shaft:
Two mild steel shafts of length 60cm and diameter varying from 24mm to 17mm as per shaft design. Both of the shafts are supported by two roller bearings of inner diameter 17mm and 24mm and outer diameter of 35mm and 42mm respectively. The centre to centre distance between two shafts is 143mm. The prime mover is connected to the upper shaft with the help of a coupling. The upper shaft being the input shaft the gear blanks are kept fixed by providing keys. The lower shaft being the output shaft the gear blanks are movable to show variable gear ratios. Metal bushes are used to fix the gear blanks at required positions on the lower shaft.

D. Base:
Base consists of two upper and lower compressed wood supports for the stability of the prototype. Two vertical post of compressed wood itself are provided to place the two mild steel shafts. On the left post two bearing seats of inner diameter 42mm and outer diameter of 52mm are there at a distance of 143mm for placing the 24mm bearings. On the right post two bearing seats of inner diameter of 35mm and outer diameter of 45mm at a distance of 143mm are there for placing the 17mm bearings. The prime mover used is an AC single phase induction motor of 1440rpm capable of producing 0.5 HP. In order to obtain the desired rpms from the prime mover its connected to an auto transformer of 10 A.

Figure 3 shows the proposed prototype of the Magnetic gearing system. It consists of a half horse power motor which is the prime mover. It is coupled to a shaft where the Magnetic gear blanks are fixed.
IV. EXPERIMENTAL PROCEDURE

A. Basic Principle:
First two gear blanks are taken. Material of gear blank is hylam sheet since it is a light weight non ferromagnetic polymer. Using an adhesive (Araldite) we are placing the magnets in alternate poles along the circumference of gear blank. One of the blank is driven by a motor which is the driving gear. Other driven gears are placed near the driven gear. Driving gears are not in contact but lie inside the magnetic field of driving gear. By this way we can transmit torque from driving gear to driven gear without any frictional loss. Gear ratio can be changed by changing the number of magnets and diameter of the gear blanks.

B. Basics Of Magnetic And Mechanical Gears:
A gear can be defined as a mechanism that transfers torque from one shaft to another shaft by the use of magnets or mechanical teeth. Some mechanical gears are very similar to magnetic gears for instance the magnetic spur gear.

![Magnetic spur gear](image1)

![Mechanical spur gear](image2)

Figure 4 shows the similarity between a Magnetic spur gear and the conventional toothed gear. Magnetic spur gear consists of magnets arranged circumferentially and the alternate attraction and repulsion helps in power transmission.

![3-D Model of gear blanks](image3)

Figure 5 shows the 3-D model of the proposed Magnetic gear. The traditional mechanical gear uses steel teeth’s to transfer torque. Gear wheel teeth have physically contact with each other, and there will be wearing on the tooth flanges. The magnetic gear does not have the same wear, because there is no direct contact. Permanent magnets on the gearing wheels transfer the torque between the two wheels. Since the magnetic gear does not have direct contact, there will be a fictive torsion spring effect between gear wheels.

The torsion spring effect can be explained by imaging one wheel fixed and the other wheel is rotated a small angle. Then there will be a certain torque interaction between the gear wheels depending on angle displacement of the second wheel. This phenomenon is illustrated on Figure 6.2 where a magnetic gear consisting of a driving gear wheel and a driven gear wheel is shown. The torsion spring phenomenon is similar to the well known torque angle characteristic effect in synchronous machines.
Figure 6 shows the torque diagram of the Magnetic gear. Gearing relationship $R_g$ depends on the number of magnets $N_{pole1}$ on the drive wheel and $N_{pole2}$ on driven wheel. This relationship can be shown as equation (1).

Most gear systems have a gearing relationship $R_g$ which is greater than one, which corresponds to high revolutions on the input shaft and low revolutions on the output shaft. Gearing relationship equation is valid for mechanical gears also if the number of magnet poles are replaced of number of teeth’s on each gearing wheel.

$$R_g = \frac{N_{pole1}}{N_{pole2}}$$  (1)

V. DESIGN OF MAGNETIC GEARING SYSTEM

A. Mathematical Modeling Of Magnetic Gear With Cuboidal Magnets:

Two cubical magnets of sides $a$, $b$, and $c$ and $a_0$, $b_0$, and $c_0$ are shown in Figure 7.

$$\phi = \frac{4L^2}{(R_z^2-R_1^2)+(R_z^2-R_3^2)}$$  (5)
B. Calculation Of Maximum Load Carried By The Magnet:

Two cubical magnets of sides length 10mm breadth 20mm and height 10mm and the distance between the magnets be 3mm, calculate the load carrying capacity between the magnet and also calculate estimate the load carrying capacity of the equivalent sector magnets. Consider the magnetic remanence value of both the magnets as 1T.

Solution: Here, L=30mm B=20mm (R₂-R₁) =H=(R₄-R₃) =c =10 mm, and Clc=3 mm. Assuming R₁=10 mm, R₂=20 mm, R₃=21 mm, and R₄=31 mm. The value of w is estimated from Eq. (5) i.e.

\[
\varphi = \frac{4L^2}{40 \times 30^2} \times \left( \frac{(R^2_2 - R^2_1) + (R^2_4 - R^2_3)}{(20^2 - 10^2) + (30^2 - 20^2)} \right) \rightarrow \varphi = 0.4562
\]

The vertical force between two cubical magnets is found by using Eq. (2)

\[
F_{y,c} = \frac{\sigma_1 \sigma_2}{4\pi\mu_0} \left( R(0) + R(0.01 - 0.01) + R(0.01) + R(-0.01) \right)
\]

Where

\[
R(\alpha) = \int \int \int \int \frac{(Y - y)}{(x - X)^2 + (y - Y)^2 + (\alpha)^2} \text{d}X \text{d}Y \text{d}x \text{d}y
\]

The value of \(F_{y,c}\) is estimated by solving the above equation in MATLAB and found to be 66.016 N. 66 N is sufficient for driving the whole gear system so we confirmed 3mm as the distance between two gear blanks.

C. Distance Between Two Gear Blanks On Same Shaft:

By analysing the magnetic field visualization and the magnetic vector plot from the 3D magnetic gear model, The magnetic field lines are concentrated only at the two sides of the cubical magnet and it has been recorded that the range of magnetic field is below 10 cm hence two magnets can be kept at a distance of 10 cm without having flux linkages. By the help of this practical calculation we kept the two gear blanks on a single shaft at a distance of 10 cm apart.

![Fig. 8.2: B-field vector plot from the 3D magnetic gear model.](image)

![Fig. 8.3: (a) magnetic field visualisation (b) pull force v/s distance graph](image)
Figure 8.2 shows the magnetic field vector plot diagram which shows the direction of the magnetic field lines. Figure 8.3(a) shows the magnetic field visualisation which shows the strength of the cubical magnet we are using. Figure 8.3(b) shows the pull force generated by two magnets and its variation according to the distance between them changes.

### I. Gear Ratios:

The prime mover motor is kept at 1000 rpm so the input shaft rotates at same speed. In order to decease and increase the output speed at our desired level we have to design the diameter and the number of magnets of meshing gears.

\[
\frac{N_{\text{input}}}{N_{\text{output}}} = \frac{D_{\text{output}}}{D_{\text{input}}}
\]

1\textsuperscript{st} gear
Input speed = 1000 rpm
Diameter of gear in input shaft = 80mm
Diameter of shaft in output shaft = 200mm

\[
\frac{1000}{N_{\text{output}}} = \frac{200}{80} \quad N_{\text{output}} = 400 \text{ rpm}
\]

Output speed = 400rpm

2\textsuperscript{nd} gear
Input speed = 1000 rpm
Diameter of gear in input shaft = 180mm
Diameter of shaft in output shaft = 100mm

\[
\frac{1000}{N_{\text{output}}} = \frac{180}{100} \quad N_{\text{output}} = 555.5 \text{ rpm}
\]

Output speed = 555.5rpm

3\textsuperscript{rd} gear
Input speed = 1000 rpm
Diameter of gear in input shaft = 200mm
Diameter of shaft in output shaft = 80mm

\[
\frac{1000}{N_{\text{output}}} = \frac{80}{200} \quad N_{\text{output}} = 2500 \text{ rpm}
\]

Output speed = 2500rpm

### E. Scope for Future:

Magnetic gears are becoming competitive alternatives to conventional gears. They present no contact and no wear. They do not produce debris and they do not require lubricant, being able to be operated at a broad range of temperature ranging from -270ºC up to 350ºC. They present intrinsic anti-jamming properties and there is a clutching effect if the applied torque exceeds a limit therefore protecting the output from overloads. This effect is completely reversible without any damage or wear.

This technology is currently increasing making it available for consideration for aerospace uses. The radically different behaviour against torque overloads, the isolation of vibrations, the absence of maintenance, the compatibility with sand or dust, broad temperature range and the through wall capability are some properties that make these devices attractive for aerospace and other future applications.

### VI. Applications of Magnetic Gears

#### A. Turbine Generators:
- Key drivers: reduce weight + increase reliability
- Non-contact gearbox or integrated gearbox / generator
- Reduce direct drive diameter

#### B. Energy Storage Flywheels:
- Commercial power utility back up
- Off-grid renewably-generated energy storage
- Automotive regenerative braking systems

#### C. Gearing For Drilling Motors:
- Convert high speed to high torque for drilling
- Isolation of drill bit axial / thrust loads from motor
- Hollow bore to allow drilling fluid flow

D. Oil Well Sub-Surface Safety Valve:
- For emergency shutoff of oil well, deep underground
- Linear gear provides force multiplication
- Reduces size / output required by hydraulics

E. Robotics:
- Easy movements arms for other parts
- Less constraints in motion
- Reliability

F. Aerospace:
- The isolation of vibrations
- The absence of maintenance
- Broad temperature range

VII. CONCLUSION

Magnetic gears afford the opportunity to provide speed and torque multiplication similar to a traditional geared gearbox or transmission, but by using magnetic attraction between rotating members rather than actual physical contact, as between gear teeth. It may be possible to greatly reduce, or potentially eliminate, lubrication requirements, compared to existing traditional gearboxes.

A magnetic gear based gearbox for winch applications could increase reliability and mission availability by reducing or perhaps eliminating wear-related gearbox failures attributable to traditional tooth-to-tooth contact.

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