A Novel High-Performance Linear Magnetic Gear

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Keywords: linear magnetic gear, linear machine, permanent magnets

The increasing demand for high force density actuators is currently being met almost exclusively by employing a leadscrew and nut to transform rotary motion to linear motion. However, an alternative approach is to employ a linear magnetic gear to increase the force capability of a conventional linear actuator. Therefore, the paper describes the design and performance of a linear magnetic gear having the tubular topology shown in Fig. 1 and whose parameters are given in Table 1.

Fig. 2 shows the variation of the maximum thrust force exerted on the low speed armature when a quasi-Halbach magnetization is employed for the high-speed armature. It can be seen that a force density in excess of 2 MN/m^3 can be achieved. Fig. 3 shows how the force density of a magnetically geared actuation system comprising a linear magnetic gear and a linear permanent magnet brushless motor varies with the gear ratio, assuming the linear motor to have a force density of 0.3 MN/m^3 and 0.6 MN/m^3 , these being typical values for naturally-cooled, and liquid-cooled permanent magnet linear brushless motors, respectively. As can be seen, the system force density for a gear ratio as low as $3.25 : 1$ can be more than 100% greater than that of a naturally-cooled linear motor, for example.

Table 1. Parameters of linear magnetic gear

Gear ratio	3.25:1
Diameter of stationary armature	90 mm
Active length of high speed armature	100 mm
Total length of stationary armature	144.4 mm

Fig. 2. Variation of maximum thrust force exerted on low speed armature with radial thickness of ferromagnetic rings and permanent magnets on high speed armature

Fig. 1. Schematic of 3.25 : 1 linear magnetic gear

Fig. 3. Variation of system force density with gear ratio for a linear magnetic gear force density of 2 MN/m^3

A Novel High-Performance Linear Magnetic Gear

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Currently, the demand for high force density linear actuators is being met almost exclusively by employing a lead-screw and nut to transform rotary motion to linear motion. This paper describes an alternative technology, viz. a linear magnetic gear, which employs rare-earth magnets and which could be used in conjunction with a conventional linear actuator. Simulation studies have shown that such a gear has a highly competitive force transmission density.

Keywords: linear magnetic gear, linear machine, permanent magnets

1. Introduction

The increasing demand for high force density actuators is currently being met almost exclusively by employing a lead-screw and nut to transform rotary motion to linear motion. However, the efficiency of such helical force transformation systems can be relatively poor, particularly for low helix angles. In addition, wear and reliability can be significant issues, and lubrication may be required. An alternative approach is to employ a linear magnetic gear to increase the force capability of a conventional linear actuator, such as a linear brushless motor. To date, however, such an approach has received little, if any, attention.

The paper describes the design and performance of a linear magnetic gear having the tubular topology shown in Fig. 1, whose principle of operation is similar to that of the rotary and linear magnetic gears which were described in (1), (2) and (3). It is shown that, when rare-earth magnets are employed, such a linear magnetic gear can have a transmitted force density in excess of 2 MN/m^3 . Thus, when combined with a linear permanent magnet brushless motor, such a magnetic gear could offer significant advantages for many applications.

2. Principle of Operation

Fundamental to the operation of the magnetic gear is the modulation of the magnetic field produced by each of the concentric tubular permanent magnet armatures by the ferromagnetic rings (pole-pieces). These are disposed such that appropriate space harmonics result in the airgap magnetic field on each side of the pole-pieces, such that the magnetic field which results from one permanent magnet armature has the same number of poles as the associated permanent magnet armature. It can be shown, (2), that the number of pole-pairs in the space harmonic flux density distribution produced by either permanent magnet armature is given by:

Fig. 1. Schematic of 3.25 : 1 linear magnetic gear

$$p_{m,k} = |mp + kn_s| \dots \dots \dots (1)$$

$$m = 1, 3, 5, \dots, \infty; \quad k = 0, \pm 1, \pm 2, \pm 3, \dots, \pm \infty$$

and that the linear velocity of the flux density space harmonics is given by:

$$v_{m,k} = \frac{mp}{mp + kn_s} v_r + \frac{kn_s}{mp + kn_s} v_s \dots \dots \dots (2)$$

where p is the number of pole-pairs on the armature, n_s is the number of ferromagnetic pole-pieces, and v_r and v_s are the linear velocity of the armature under consideration and the linear velocity of the pole-pieces, respectively. It will be noted that either the low speed permanent magnet armature or the ferromagnetic rings may be held stationary. However, in Fig. 1 it is assumed that the low speed armature is stationary.

From equation (2), it can be seen that the velocity of the space harmonics, which result due to the introduction of the ferromagnetic rings, viz. $k \neq 0$, is different to the velocity of the armature whose magnetic field they modulate. Therefore, in order to transmit thrust force at a different velocity,

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the number of active pole-pairs on the other permanent magnet armature must be equal to the number of pole-pairs in a space harmonic for which $k \neq 0$. Since the combination $m = 1, k = -1$ results in the highest asynchronous space harmonic field, the number of pole-pairs of the other armature must be equal to $(n_s - p)$. The gear ratio is then given by:

$$G_r = \frac{n_s - p}{p} \quad (3)$$

when the modulating ferromagnetic rings are held stationary, ie. $v_s = 0$. On the other hand, if the low speed permanent magnet armature is held stationary, and the thrust force is transmitted to the ferromagnetic rings, the gear ratio becomes:

$$G_r = \frac{n_s}{p} \quad (4)$$

This may be the preferred arrangement since it simplifies the mechanical design of the gear and enables a higher force to be transmitted, the increase being dependent on the gear ratio.

3. Simulation Studies

Table 1 gives the parameters which have been assumed for the linear magnetic gear shown in Fig. 1, which is equipped with radially magnetised sintered NdFeB permanent magnets having a remanence of 1.25 T. 2-dimensional axis-symmetric magnetostatic finite element analysis has been employed to predict the flux density waveforms and the force transmission capability of the gear.

3.1 Flux Density Waveforms Fig. 2 shows the variation of the radial component of flux density due to the high speed, low pole number permanent magnet armature in the airgap adjacent to the stationary high pole number armature, whilst Fig. 3 shows the corresponding space harmonic spectrum. It can be seen that the presence of the ferromagnetic rings results in a number of asynchronous, viz. $k \neq 1$, space harmonics, the largest of which is the 9 pole-pair space harmonic, ($m = 1, k = -1$), which interacts with the 9 pole-pair

permanent magnets on the stationary armature to transmit a thrust force.

Similarly, Fig. 4 shows the variation of the radial component of flux density due to the permanent magnets mounted on the stationary armature in the airgap adjacent to the high speed armature, whilst Fig. 5 shows the corresponding space

Fig. 2. Variation of radial flux density, due to high speed permanent magnet armature, in airgap adjacent to stationary armature

Fig. 3. Space harmonic spectrum of radial flux density, due to high speed armature, in airgap adjacent to stationary armature

Fig. 4. Variation of radial flux density, due to stationary armature, in airgap adjacent to high speed armature

Table 1. Parameters of linear magnetic gear

Number of pole-pairs on high speed armature	4
Number of active pole-pairs on stationary armature	9
Number of active ferromagnetic rings	13
Gear ratio	3.25:1
Diameter of stationary armature	90 mm
Diameter of high speed armature	56 mm
Active length of high speed armature	100 mm
Total length of stationary armature	144.4 mm
Air-gap length	1 mm
Radial thickness of stationary armature back-iron	5mm
Radial thickness of high speed armature magnets	L_h
Radial thickness of ferromagnetic rings	L_f

Fig. 5. Space harmonic spectrum of radial flux density, due to stationary armature, in airgap adjacent to high speed armature

Fig. 6. Variation of maximum thrust force exerted on low speed armature with radial thickness of ferromagnetic rings and permanent magnets on high speed armature

harmonic spectrum. Again, it can be seen that the presence of the ferromagnetic rings results in a dominant 4 pole-pair asynchronous space harmonic, ($m = 1, k = -1$), which interacts with the 4 pole-pair permanent magnets on the high speed armature to transmit thrust force.

3.2 Thrust Force Fig. 6 shows the variation of the maximum thrust force exerted on the low speed armature with the radial thickness of both the high speed armature permanent magnets and the ferromagnetic rings when the magnets are radially magnetised, whilst Fig. 7 shows the variation of the thrust force which is exerted on the low speed and high speed armatures as they move linearly. It can be seen that the transmitted force remains fairly constant over a stroke of ~ 20 mm.

One way of increasing the force density is to employ quasi-Halbach magnetized magnets on the high-speed, low pole number armature, such that each pole comprises a radially magnetised magnet and an axially magnetised magnet. By way of example, Fig. 8 shows the variation of the maximum thrust force exerted on the low speed armature with the ratio of the axial length of the radially magnetized ring magnets to the pole-pitch, α_r , on the high speed armature, the

Fig. 7. Variation of maximum thrust force exerted on low speed and high speed armatures, $L_h = 5$ mm, $L_f = 5$ mm

Fig. 8. Variation of maximum thrust force on low speed armature with α_r . ($L_h = 5$ mm, $L_f = 5$ mm)

Fig. 9. Variation of maximum thrust force exerted on low speed armature with radial thickness of ferromagnetic rings and permanent magnets on high speed armature. (Halbach magnetization)

Fig. 10. Variation of maximum thrust force exerted on low speed and high speed armatures. (Halbach magnetization, $\alpha_r = 0.7$, $L_h = 5$ mm, $L_f = 5$ mm)

Fig. 11. Variation of system force density with gear ratio for a linear magnetic gear force density of 2 MN/m^3 .

magnets on the low speed armature being radially magnetised. It can be seen that the optimum value of α_r is 0.7. Fig. 9 shows the variation of the maximum thrust force which is exerted on the low speed armature with the radial thickness of the high speed armature permanent magnets and the ferromagnetic rings, for $\alpha_r = 0.7$. It can be seen that the quasi-Halbach magnetization results in a significantly higher thrust force than that which was developed when radially magnetized magnets were employed. Fig. 10 shows the variation of the thrust force which is exerted on the low speed and high speed armatures as they move linearly. As can be seen, a force density in excess of 2 MN/m^3 can be achieved.

Fig. 11 shows how the force density of a magnetically geared actuation system comprising a linear magnetic gear and a linear permanent magnet brushless motor varies with the gear ratio, assuming the linear motor to have a force density of 0.3 MN/m^3 and 0.6 MN/m^3 , these being typical values for naturally-cooled, and liquid-cooled permanent magnet linear brushless motors, respectively. As can be seen, the

system force density for a gear ratio as low as 3.25 : 1 can be more than 100% greater than that of a naturally-cooled linear motor and more than 50% greater than that of a liquid-cooled linear motor. Therefore, the combination of a linear magnetic gear with a permanent magnet linear motor results in an actuation system, which has a significantly higher torque density than the motor alone.

4. Conclusions

The effects of design parameters on the thrust transmission capability of a high performance linear magnetic gear have been presented. It has been shown that, by employing a quasi-Halbach magnetized rare-earth magnets on the high-speed armature, a thrust force density of $\sim 2.0 \text{ MN/m}^3$ can be achieved. It has also been shown that a high system force density for a combined linear magnetic gear and linear electrical machine can be achieved, even with a relatively low gear ratio.

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