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Magnetic gears for high-precision mechatronic applications

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Abstract
Because of their contactless torque transmission mechanism, magnetic gears are advantageous over mechanical gears in terms of efficiency, torque overload protection and acoustic noise. This paper evaluates the prospects of magnetic gears for high-precision mechatronic applications. Through design examples, the static and dynamic performances of magnetic gears are presented and compared with that of commercial high-performance mechanical gears.

Keywords: Magnetic gears, Mechatronics, Mechanical gears, Design, Static, Dynamic

1. Introduction

The forces acting between magnets of different polarities can be utilized to create a gearing mechanism. In its simplest form, a magnetic gear can be realized by configuring two permanent magnet (PM) arrays as depicted in Fig. 1 (a), which result in a mechanism similar to that of mechanical spur gears. However, only a small circumferential portion of each PM array in Fig. 1 (a) contributes to the torque transmission, implying ineffective use of the available PMs. A significantly better utilization of the PM arrays in a magnetic gear can be achieved through a topology shown in Fig. 1 (b) [1], in which all of the PMs contribute to the torque transmission.

The ferromagnetic pole-pieces in Fig. 1 (b) are used to modify the spatial harmonic content of airgap magnetic flux density that is produced by a PM array. This is illustrated by an example in Fig. 2, showing that the pole-pieces introduce a new dominant harmonic component that corresponds to the number of pole pairs of the outer PM array in Fig. 1 (b). The new harmonic component rotates at a lower speed than the inner PM array, which creates a gearing effect.

The goal of this paper is to show the prospects of magnetic gears based on the topology in Fig. 1 (b) to be used in high-precision mechatronic/robotic applications. This is done through design examples and comparison with commercial high-performance mechanical gears of similar transmission ratio, torque and dimensions. The aspects to compare are static and dynamic performance criteria, i.e. torque density, mass, efficiency and resonant frequency.

2. Operating modes and transmission ratio

The inner PM array in Fig. 1 (b) acts as the inner (high-speed) rotor, while either the outer PM array or the set of ferromagnetic pole-pieces can act as the outer (low-speed) rotor. This results in two possible operating modes, i.e. stationary pole-pieces and stationary outer PM array, each with its own transmission ratio as presented in Table 1, where P_i and P_o are number of inner and outer PM array pole pairs, respectively, and $Q = P_i + P_o$ is the number of pole-pieces. The operating mode based on the stationary outer PM array is selected in this paper, due to the higher transmission ratio (see Table 1) and the lower moment of inertia of the rotating pole-pieces, compared to the outer PM array.

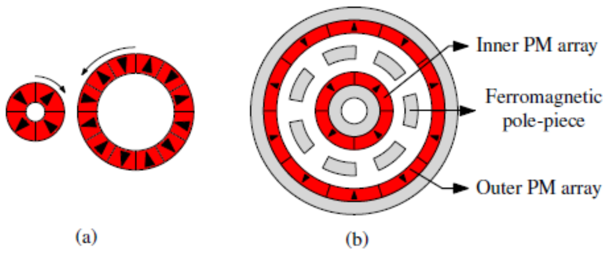

Figure 1. Magnetic gear: (a) spur-gear based topology. (b) Investigated topology.

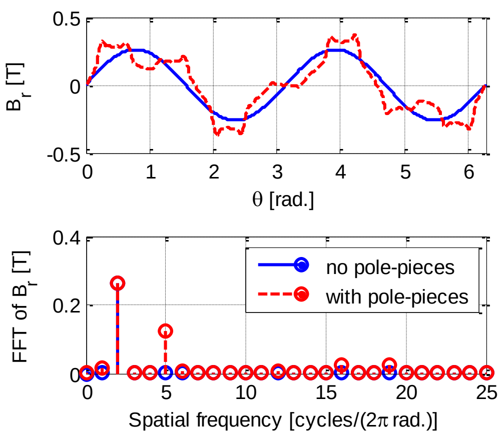

Figure 2. Airgap radial magnetic flux density B_r and its harmonic content, produced by the inner PM array of the gear in Fig. 1 (b).

Table 1. Magnetic gear operating modes and their corresponding transmission ratios.

Operating mode	Transmission ratio
Stationary pole-pieces	$N_{mg,1} = \frac{Q - P_i}{P_i} = \frac{P_o}{P_i}$ (1)
Stationary outer PM array	$N_{mg,2} = \frac{Q}{P_i} = \frac{P_o + P_i}{P_i}$ (2)

3. Modelling and Design

The electromagnetic behaviour of the magnetic gear is analytically modelled through Fourier analysis [2], which is validated by 2D FEM (Finite Element Method) model in a simulation result in Fig. 3, from which it is evident that the outer rotor would slip if the load torque exceeds the peak of the sinusoidal torque characteristic. Using the analytical model, the design is performed through an optimization algorithm called interior-point method. Eight magnetic gears are designed, each with the objective of a minimum total mass, while fulfilling constraints such as fixed outer diameter and peak torque values, based on the selected commercial mechanical gears in Table 2. For each mechanical gear, two magnetic gears are designed with inner PM array pole pair numbers $P_i = 3$ and 4. The rest of the design specifications and constraints are presented in Table 3.

4. Results

The torque density and mass of the optimized magnetic gears in Fig. 4 consider twice of the volume to account for the housing, bearings and shafts. It can be seen that magnetic gears c-d, f-h (see Table 2) have comparable or better performance than the planetary gears. The mechanical gears in Table 2 have a maximum efficiency of 90%, while the magnetic gear efficiency can be significantly higher as apparent from Fig. 5. Note that the magnetic gear losses are mainly contributed by eddy current and hysteresis loss (see [3] for a further discussion).

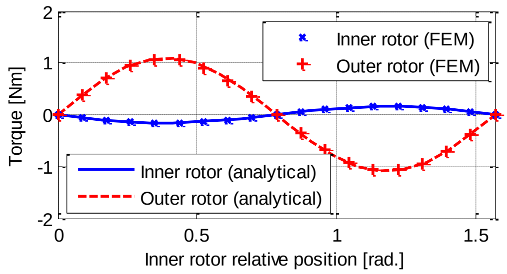

Figure 3. Magnetic gear torque as a function of the inner rotor position relative to the outer rotor.

Table 2. Chosen mechanical planetary gears from Maxon and the corresponding magnetic gear transmission ratios.

Mechanical gear		Magnetic Gear
Type	**Trans. Ratio**	**Trans. Ratio**
GPX 26 (Diameter = 26 mm, peak torque = 1.1 Nm)	3.9:1	3.67:1, $P_i = 3$ (a)
		3.75:1, $P_i = 4$ (b)
	6.6:1	6.33:1, $P_i = 3$ (c)
		6.75:1, $P_i = 4$ (d)
GPX 32 (Diameter = 32 mm, peak torque = 2 Nm)	3.9:1	3.67:1, $P_i = 3$ (e)
		3.75:1, $P_i = 4$ (f)
	6.6:1	5.25:1, $P_i = 4$ (g)
		5.67:1, $P_i = 3$ (h)

Table 3. Magnetic gear design specifications and constraints.

Specification	**Value**
PM remanence and rel.	1.41 T
PM relative permeability	1.05
PM density	7500 kg/m^3
Electrical steel type	1010
Electrical steel density	7870 kg/m^3
Constraint	**Value**
Cogging	≤ 1% of peak torque
Magnetic flux density in cores	≤ 2 T
Radial height of airgap	≥ 0.2 mm
Radial height of PMs and cores	≥ 1 mm

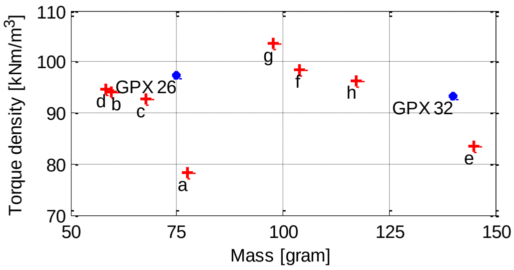

Figure 4. Torque density and mass of the gears in Table 2.

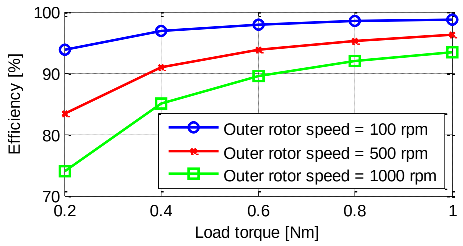

Figure 5. Efficiency of magnetic gear (a) in Table 2.

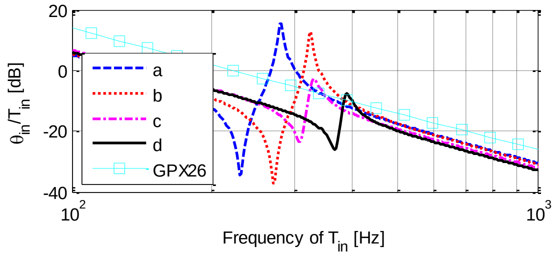

Figure 6. Frequency response from inner rotor torque T_{in} to inner rotor position θ_{in} for magnetic gears a-d and the GPX 26 mechanical gear.

Compared to mechanical gears, magnetic gears have inherently low rotational stiffness that causes a resonance. The stiffness is calculated by linearizing the torque characteristic in Fig. 3 at 0 rad., and is proportional to the peak torque, inner rotor PM pole pair and transmission ratio [2]. Figure 6 shows that resonance in the magnetic gear frequency response (from inner rotor position to inner rotor torque) appears in the range of 200 Hz – 400 Hz, for gears a-d in Table 2, which have similar values of load inertia. The resonance could pose an issue in a closed-loop system, as it limits the control bandwidth.

5. Conclusions

In this paper, magnetic gears are designed to be compared with commercial mechanical gears in terms of static and dynamic performance criteria. Based on the comparison, magnetic gears can have comparable or better torque density, mass and efficiency with respect to mechanical gears. A potential drawback of magnetic gears comes from the dynamic aspect due to resonance, although this is application-specific. As such, magnetic gears can serve as competitive alternatives to mechanical gears in high-precision mechatronic applications.

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