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ORIGINAL ARTICLE

A bearingless coaxial magnetic gearbox

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Abstract Recently, magnetic gearboxes (MGBs) are serious contenders to their conventional mechanical counterparts in terms of reduced maintenance requirements, improved reliability, tolerance to mechanical inaccuracies, and inherent overload protection. MGBs are preferably employed in high speed applications and compact harsh environments subjected to severe shock and vibration. A high gear ratio MGB is also a suitable candidate for single stage high-speed transmission applications such as helicopter power transmissions. In this paper, the conventional planetary magnetic gearbox is equipped with a three-phase winding to provide additional magnetic levitation capabilities besides torque transmission, thus creating a bearingless MGB configuration. This was achieved by adding a three-phase winding in the space between the ferromagnetic pieces. The current in this additional winding is controlled to provide decoupled axial forces irrespective of the transmitted mechanical power. This feature is important to reduce the mechanical losses especially for high-speed rotors and can be a viable method for vibration suppression.

1. Introduction

The magnetic gearbox is a recent technology that offers many advantages over conventional mechanical gearboxes including reduced maintenance and improved reliability, lack of lubrication requirements, precise peak torque transmission, inherent overload protection, physically isolated input and output shafts, misalignment tolerance, and low acoustic noise and vibration [1,2]. In the available literature, different linear and rotary magnetic gear topologies have been investigated [1–8]. One of the promising configurations is the rotary planetary configuration initially proposed in [5]. A detailed comparison between this magnetic gear type and a mechanical planetary gearbox is introduced in [9]. The study shows a comparable performance between the two types with obvious benefits offered by magnetic gearbox inherent in its noncontact magnetic structure. On the other hand, torque density of this configuration falls significantly for gear ratios higher than about 20:1. In [3], a novel magnetic harmonic gearbox, which is similar to a mechanical harmonic gearbox, was introduced to address the higher gear ratio limitations of the planetary magnetic gearbox. An active torque density reaching 150 kN m/m^3 per stage can be achieved when rare-earth permanent magnets are used in this configuration. Moreover,

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Nomenclature

p	number of pole-pairs
n_s	number of ferromagnetic pole pieces
N	rotor speed (rpm)
ω	rotor angular speed (rad/s)
ω_v	angular frequency of levitation winding current (rad/s)
F	force (N)
B	flux density (T)
R	inner air gap radius (m)
L	gear stack length (m)
μ_0	air permeability (H/m)
θ	air gap peripheral angle (rad)
δ	shift angle between the different flux components
G_r	gear ratio
C_T	cogging torque factor
I	current (A)
J	current density (A/mm^2)
A_s	slot area (mm^2)
a_c	conductor cross-sectional area (mm^2)
A_c	total conductor area (mm^2)
k_{fill}	slot filling factor
T	number of conductors per slot
ϕ	rotor position
x, y	xy radial displacements (m)

Subscript

l	low speed rotor
h	high speed rotor
g	air gap
v	levitation winding
α, β	winding stationary frame

ripple free transmitted torque was obtained. The origin for this cycloid/harmonic gear concept is described in [10]. Despite their advantages, magnetic gears have received minimal industrial attention, mainly due to the perceived initial cost added by permanent magnets. However, their advantages may warrant their application, especially when combined with a high-speed electrical machine resulting in a desirable size/weight and cost effective solution. Hence, MGBs were proposed in applications like wind energy with high-speed generators [11] and contra-rotating tidal turbines [12].

In high-speed electrical machines, the critical speed is a serious problem due to the significant induced vibration on the rotor structure at elevated speeds [13]. The self-bearing or bearingless machine is an electromagnetic device that supports its own rotor by magnetic forces generated from windings on its stator [14]. When compared with conventional active magnetic bearings, bearingless drives offer many advantages which are realized as a result of the integration of a radial magnetic bearing and a motor, including compactness, low cost, and higher power density [15].

The application of bearingless motors in vibration suppression was proven to be effective because the magnetic force is generated within the motor itself [13–15]. The concept of bearingless motors has been developed theoretically in [16]. Since then, the concept has been applied to synchronous reluctance, induction, permanent magnet, disc-type bearingless, homopolar, hybrid, and consequent-pole bearingless drives [17–19]. Bearingless motors are also compatible with the recent trend for miniaturization and the increasing cleanness specifications in chemical, pharmaceutical, biotechnology, and semiconductor industry applications demanding high-purity process environments [20].

In the recent literature, different types of bearingless motors with different winding structures, different converter topologies, and different control methods have been presented to comply with various applications [20–24]. The radial force generated from the bearingless motor has also been used for equipment shaft vibration suppression to go through the first bending critical speed [15,25]. Two kinds of magnetic forces are generated for vibration suppression: spring force, which acts in the opposite direction of the rotor radial displacement, and damping force, which is proportional to the derivative of the negative rotor radial displacement [15,25].

In this paper, the conventional planetary MGB, with a $2p_h$-pole high-speed rotor shown in Fig. 1a is equipped with a $(2p_h - 2)$-pole, 3-phase winding embedded in the space between the ferromagnetic pole-pieces, as shown in Fig. 1 [26,27]. The selected pole-pairs combination between the high-speed rotor and the new levitation winding enables the development of an average unbalanced magnetic pull [17,26]. Hence, the current in this winding can be used to produce controllable radial forces acting on the high speed rotor to provide the MGB with additional magnetic levitation capabilities, emulating a self-aligning bearingless magnetic gearbox.

Mechanical self-aligning bearingless planetary gears (SABP) have been proposed for helicopter applications since the 1960s [28–30]. Many of the advantages that emerged from the use of the mechanical SABP are similar to those generally offered by its magnetic counterpart, such as: eliminating planet bearing power losses and failures, providing sufficient flexibility and self-centering to give good load distribution between planet pinions, effectively isolate planetary elements from housing deflections, and increasing operating time after loss of lubricant. A prototype MGB with the proposed modification is designed based on finite element analysis and simulated to validate the proposed idea [31].

2. Proposed magnetic gearbox

The proposed modifications to a conventional MGB are shown schematically in Fig. 1. The new structure includes a $(2p_h - 2)$-pole levitation winding. A polymer carrier is used to house both the ferromagnetic pole-pieces and the $(2p_h - 2)$-pole three-phase winding. The number of ferromagnetic pole-pieces, n_s, equals the number of both inner and outer magnet pole-pairs, $n_s = p_l + p_h$ [1]. For the magnetic gearbox with a 38/4 ($2p_l/2p_h$) pole combination shown in Fig. 1, the required number of ferromagnetic pole-pieces will be 21. In