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An investigation on the electromagnetic design optimization of rotary micromachines with double-layer permanent magnets☆

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ABSTRACT

Electromagnetic design optimization of axial-flux rotary micromachines utilizing double-layer permanent magnets is presented and applied to a micro-scale generator/spirometer currently under development. Double-layer magnet configuration enables the use of two stators in a rotary micromachine, and hence offers performance enhancements in such devices. For an efficient transduction, number of magnetic poles should be carefully selected to obtain maximum flux density in a given device geometry, where magnetic reluctance and leakage act as two competing effects. This optimization has been performed through electromagnetic finite element simulations over a range of MEMS geometries. It was shown that the optimum number of magnetic poles varies from 22 to higher than 32 depending on specific magnet dimensions. Experiments on a manufactured magnet were performed and compared with simulation results. The analysis and results reported here shed light on the efficient design of magnetic micromachines in similar scales.

1. Introduction

The use of permanent magnets offers many advantages over other type of magnetic architectures in rotary micromachines at the millimeter and lower scales. In particular, permanent magnet-based designs do not suffer from size reduction in terms of magnetic performance [1,2], contain a free source of magnetic flux [3], lead to high torques [4], and are compatible with the planar nature of microfabrication techniques [5]. Accordingly, such designs have been used in the development of numerous microdevices including motors, power generators, and various sensors.

Permanent magnets in rotary micromachines are traditionally made in ring shapes with multiple poles, integrated into the rotor, and designed to provide axial flux [1–21], where the magnetic flux density vector is parallel to the axis of rotation. In general, a stator with micro coils beneath the magnets performs electrical-to-mechanical or mechanical-to-electrical power conversion in accordance with electromagnetic induction principles. Number of magnetic poles used in the device is an important factor defining the final conversion performance. One such device utilizing SmCo magnets was developed as a micromotor [4]. Different designs with 8 and 12 magnetic poles were implemented, providing output torques up to 3 μN m. In-depth mathematical analysis on three-dimensional magnetic field distribution as well as the rotor torque have been reported [6,7]. Magnet-based axial-flux architectures have also found extensive use in electrical power generators. An energy harvester that can extract energy from air flow was reported by Holmes [8]. Output power up to 1.1 mW was demonstrated on the stator with 10 NdFeB magnets incorporated into the polymer rotor. Several research groups presented similar designs using SmCo and NdFeB magnets with magnetic pole numbers ranging from 8 to 30, and reported the effect of pole number on final performance [9–12]. Milliwatts to watts of electrical power were demonstrated depending on the maximum rotational speed and active device area. In parallel, Arnold developed an axial-flux microgenerator with integrated soft magnetic materials for higher magnetic flux density within the stator. Up to 12 W of AC power was achieved with eight pole SmCo magnets having a diameter of 9.5 mm [5,13,14]. The same design with four pole NdFeB magnets was miniaturized down to a diameter of 2 mm in [15], resulting in a total AC output power of 6.6 mW. The author of this work presented the first integrated microgenerator using novel microball bearings in [16–19]. Using 10 pole NdFeB magnets, 5.6 μW was demonstrated at relatively lower speeds [16]. Finally, magnet-based axial-flux designs are also used in sensors. A peak expiratory flow meter was developed to monitor and diagnose respiratory disorders in humans [20]. The cm-scale device with eight pole NdFeB magnets was shown to measure the expiratory strength, which is related to asthma and other associated diseases.

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We are currently developing a MEMS-scale turbo generator/spirometer capable of harvesting up to 10 mW from normal exhalation, as well as measuring peak exhalation flow rate and total air intake to monitor asthma disease. In general, our design follows the axial-flux multiple-pole permanent magnet architecture due to the advantages mentioned above as well as its compatibility with planar microfabrication processes. A major feature and novelty of this device is that, unlike previous demonstrations of axial-flux micromachines with single-layer permanent magnets summarized above, our design employs double-layer permanent magnets incorporated in a silicon rotor. This design enables electromagnetic transduction using two stators located above and below the rotor, facing the two layers of permanent magnets. This allows for the exploitation of magnetic flux lines on both sides of the rotor at once, and hence, results in higher volumetric power density and improved performance. In addition, compared to single-layer magnets with two stators in [8], double-layer design does not require compliant rotor substrates or securing with heat treatment that may be detrimental for the magnetization of magnets, and provides a robust scheme for magnet integration. Hence, it is highly expected that double-layer magnet architecture, which is common in larger-scale motors and generators, will be frequently utilized in future MEMS-scale rotary machines. Similar to the previously reported devices with single-layer permanent magnets, efficient design of rotary micromachines housing double-layer magnets requires a thorough investigation on the magnetic field distribution and number of poles to maximize the device performance. Accordingly, this work focuses on magnetic flux density analysis and the design optimization of the number of magnetic poles in double-layer permanent-magnet-based rotary micromachines. Initial results on the design of this device as a respiration harvesting power generator was reported in Eurosensors 2014 conference [21]. In this paper, we broaden the device application to include spirometers through changes in geometrical design, expand our numerical analysis to a wide range of MEMS geometries, and present experimental results on the selected device geometry. The analysis and findings reported in this paper will be instrumental in the future design of similar micromachines.

2. Design

Our device consists of three main components: (i) a rotor, (ii) a stator, and (iii) microball bearings that enable mechanical rotation (Fig. 1). Both the rotor and the stator will be made of silicon, for which most standard microfabrication techniques have been developed. The rotor has turbine blades on the sides as well as trenches etched on top and bottom faces to contain microballs and permanent magnets (Fig. 1a). The magnets are selected to be off-the-shelf NdFeB components that can provide a remanent magnetic flux density of as high as 1.4 T. Similar to previously reported magnetic micromachines, the magnet geometry is determined to be ring-shaped with multiple magnetic poles to provide axial flux to the stator. The stator has planar copper micro coils, dielectric layers for electrical isolation, and microball trenches (Fig. 1b). Two stators will be placed above and below the rotor for dual-layer and high-performance operation (Fig. 1c). The microball bearings are off-the-shelf stainless steel components with a diameter of 500 μm, and sandwiched between rotor and stator trenches leaving a small air gap between the rotor and stator surfaces. The rolling motion of the microballs leads to low friction and wear that are crucial for the performance and lifetime of dynamic MEMS devices [22–24]. A schematic of the assembled device is shown in Fig. 1c.

During generator- or sensor-type of operation, tangential gas flow leads to the rotation of the turbine rotor together with the magnets. This induces voltage on radial coils of both stators in accordance with the electromagnetic induction principle;

$$V_{coil} = \frac{d}{dt}\int B \times dA \qquad (1)$$

where V_{coil} is the open circuit voltage induced on a radial coil loop with a given area A. For a device with P number of magnetic poles measuring r_{out} and r_{in} in outer and inner radii, respectively, Eq. (1) can be reduced to

$$V_{OC} = \frac{P \times N \times B_{avg} \times \pi \times (r_{out}^2 - r_{in}^2) \times \omega}{60} \qquad (2)$$

where N is the number of turns-per-pole on planar coils, ω is the rotational speed in rotations per minute, and B_{avg} is the average magnetic flux density on the stator surface provided by a single magnetic pole [13–16]. For motor-type of operation, the procedure is reversed and a voltage is applied on the micro coils, resulting in a magnetic field that interacts with the B_{avg} of permanent magnets to create rotor torque. In Eq. (2), N, r_{out}, r_{in}, and ω can be independently chosen depending on the device geometry and desired performance, while the remaining parameters P and B_{avg} are correlated since the selection of P has direct effect on B_{avg}. Irrelevant of the type of operation, high performance is desired for a microscale generator, sensor, or a motor. Therefore, number of poles should

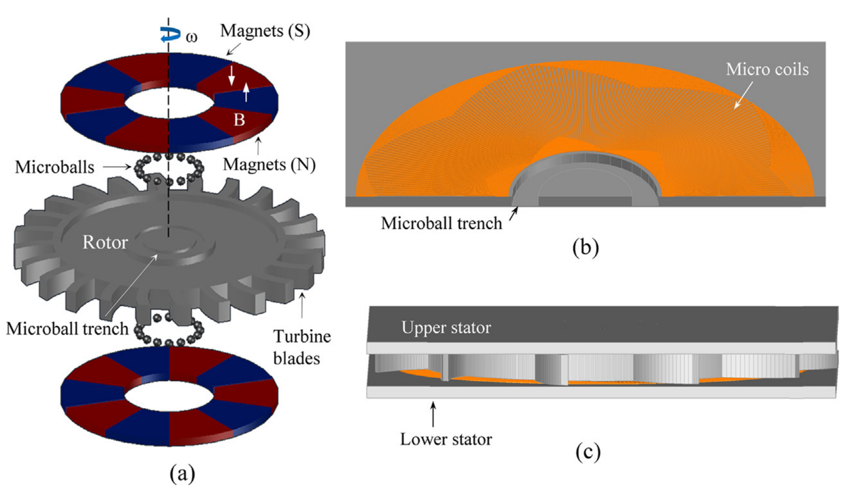

Fig. 1. (a) Exploded view of the turbine rotor showing the axis of rotation, axial-flux ring-shaped NdFeB magnets with multiple poles, stainless steel microballs, and microball trench, (b) cut-away view of the stator showing micro coils and microball trench (isolating layers are not shown), and (c) assembled device with two stators above and below the turbine rotor.