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Batch-fabrication and characterization of miniaturized axisymmetric electropermanent magnets

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Abstract. This work describes the simulation, batch fabrication, functional demonstration, and magnetic field/force characterization of highly miniaturized ~3.8 mm³ axisymmetric electropermanent magnets (EPMs). Two different bonded high-coercivity, rare-earth permanent magnet powders (~15 µm SmCo₁₇ particles and 6 µm NdFeB particles) were evaluated for the fabrication of the fixed magnets in the EPM, reaching latching force on/off ratios of 191:1 and 303:1 respectively. Compared to conventional side-by-side architecture, the axisymmetric design provides: 1) symmetric magnetic field along the magnetization axis, as opposed to the asymmetric fields in the typical transverse configuration, 2) higher and controllable latching force in a smaller volume, and 3) a path for further batch-microfabrication and system integration.

1. Introduction

An EPM is a switchable magnet [1] that only consumes power during transition between the on/off states. The EPM structure comprises a switchable magnet and a fixed magnet, which are sandwiched between two soft magnetic cap plates. The switchable magnet switches its magnetization direction to turn “on” or “off” a magnetic latching field. Application drivers for miniature EPMs include actuators/latches for microrobots and programmable matter [2], switchable magnets for microfluidic devices [3], microgrippers [4] and more. The EPM makes use of a pulse of current in a coil to flip the magnetization of one of the pair [5]. Figure 1 compares the traditional side-by-side EPM (transversal field [2–4]) vs. the new (axisymmetric field) architecture. The axisymmetric architecture aims to generate stray B fields and latching forces along the axis, using two concentric permanent magnets and two soft magnetic cap plates. This work focuses on a design and fabrication of a novel sub-millimeter axisymmetric EPM architecture and a fabrication technique that is amenable to miniaturization, building on the theory and design principles previously proposed by the authors in [6].

2. Simulations of the Axisymmetric EPM

Using 2D simulations in COMSOL Multiphysics, the B fields and latching forces of both architectures are studied as a function of several design variables: outer radius, permanent magnet aspect ratio and radius ratio, and cap plate thickness. For this investigation, the following materials were assumed: grade N52 NdFeB as fixed inner magnet, grade 5 Alnico for the outer switching magnet, and mild/low-carbon steel (AISI 1018) for the cap plates. The cap plate thickness was found to be an important variable for tuning the on/off latching force ratio Figure 1b shows the final proposed
dimensions as a function of the magnetic layer thickness (T). These dimensions were selected to maximize the on/off latching force ratio for a given cap plate thickness.

Figure 1. (a) Operational concept of the conventional and new axisymmetric EPM architectures showing the off and on states. (b) Example EPM configuration yielding maximum latching force on/off ratio (a 3T/2 thickness in cap plates will yield 450 force ratio).

Simulations of the stray magnetic field of the optimal EPM evidence ~10x difference in B field near the EPM poles in the on/off states (Figure 2a). Figure 2b shows the magnitude of the on/off B-fields along the central axis with and without the cap plates. Additional modeling is used to predict the latching force to a semi-infinite steel plate. Figure 2c shows how the on/off latching force ratio can be tuned by changing the thickness of the cap plates. Simulations of the new configuration (dimensions used in Figure 1b suggest an on/off force ratio of 450, with the ability for tuning this ratio from 1 up to 784, for sizes between 8 mm$^3$ and 34 mm$^3$, respectively. These results suggest the new axisymmetric design may afford hundred-fold higher latching force ratio than conventional EPM architectures in 1/10th the volume.

Figure 2. 2D axisymmetric COMSOL simulation. (a) B field norm contour plots. (b) Comparison of on/off fields for EPM with and without cap plates. (c) Latching force generated by different EPM’s (on and off states) vs. thickness of the steel plates.

3. Fabrication of the Axisymmetric EPM

In the axisymmetric EPM, a ring-shaped switchable magnet surrounds a cylindrical fixed magnet. The concentric magnets are fabricated by punching ~1 mm diameter holes (using a cutting cannula) in
0.8-mm-thick rubber-bonded iron oxide substrates (which forms the switchable magnetic material), previously demagnetized. Fixed magnets are fabricated on these holes by bonding high-coercivity, rare-earth permanent magnet powders (~15 µm SmCo17 particles or 6 µm NdFeB particles) and cyanoacrylate glue as bonding agent (applied on both sides), following technique described in [7]. Finally, a ~2 mm outer ring is punched, resulting in two-magnet assembly called EPM core (Figure 3). For the fully assembled EPMs, two steel cap plates (shunt) 125 µm thick were glued top and bottom of the magnet before punching the EPM core to guaranty self-align and uniform diameter of cap plates.

Figure 3. Fabrication of the EPM core, (a)Top view and (b) cross section. (c) Frontal view of the EPM including cap plates. (d) Size comparison.

4. Characterization of the Axisymmetric EPM

EPM cores are magnetically characterized by using vibration sample magnetometer (VSM, ADE Technologies EV9). Figure 4 presents a comparison of the magnetization curves for the EPM core (without caps) and the individual components (switchable and fixed bonded magnets). The SmCo EPMs yielded higher remanence ($\mu_0 M_r = 117$ mT) and lower intrinsic coercivity ($H_{ci}=210$ kA/m) than the NdFeB EPMs (75 mT and 252 kA/m).

Figure 4. Second quadrant magnetization curve (VSM) of two EPM core configurations and its components. Each graph represents the magnetization of the bonded magnet, the switchable magnet and the fabricated EPM core for: (a) SmCo and (b) NdFeB EPM cores.

Additional magnetic characterization is performed by magneto optical images (MOI) and using a pulse magnetizer to switch the EPM cores from on state (pulsing 7 T in the axial direction) to off state (by pulsing ~700 mT for SmCo or ~440 mT for NdFeB EPMs). MOI characterization (Figure 5a) of EPMs at on/off states, demonstrates there exists a reversal magnetic field (>300 mT for SmCo or >430 mT for NdFeB) capable to reverse the magnetization of the switchable magnet without affecting the fixed magnet. Cross section measurements of the B field (Figure 5b) suggest that the average on/off ration of the magnetic cores for the SmCo (27.3 mT/6 mT) and NdFeB (23 mT/8.3 mT) EPM cores are 4.6 and 2.8 respectively.
From the MOI images it is possible to calculate the magnetic flux (in units of nWb) produced by the EPM core when magnetized at different reversal magnetic fields (Figure 5c) and to report the magnetic flux on/off ratios. A full magnetization of (7 T) was always applied before applying different reverse magnetic fields (using VSM) to each EPM core before measurement. Figure 5c demonstrates that it exists a reversal magnetic field that cancel completely the magnetic flux of the EMP. This is a prove of concept of the feasibility of obtaining an “off” state from the EPM. This reversal magnetic field to turn the EPM off is >430 mT for the NdFeB sample and >300 mT for the SmCo sample.

Fully assembled EPMs with the steel cap plates were also used to measure the magnetic flux in the on/off state (by applying the reversal magnetic fields described above). The proof of concept of a EPM that can be turned “on” and “off” was demonstrated and magnetic flux on/off ratio of ~2 were achieved for both samples (NdFeB and SmCo).

**Figure 5.** Stray magnetic field (MOI) for on and off states of the EPM. Two configurations with different bonded magnets were measured: NdFeB and SmCo. (a) top view MOI images and (b) cross section measurement over the X axis (c) Calculated net magnetic flux produced by two EPM configurations (NdFeB and SmCo) for different reversal fields. Inset shows selected MOI images from which the magnetic flux was calculated. Magnetization values were selected as a function of each fixed magnet coercivity (Hc).

**Figure 6.** The demagnetization strength that turns each of the electropermanent magnets off was found from this graph by identifying the demagnetization state of each one that generated the lowest surface force. (b) Measured force at different distances from the EPM surface for on/off states.

An assemble of microbalance (Explorer 2, Ohaus) with an automated 3D micro positioner (build on house with Newport DC servo controllers) was implemented as a variation of experiments proposed by [8], to measure the latching force between the EPM and an approximate infinite ferromagnetic plate.
(mild/low-carbon steel AISI 1018). By cautiously lowering the EPM over the ferromagnetic plate, the latching force will raise the plate away from the balance and the force will be register as weigh in the balance. Figure 6a illustrate the latching force of the EPMs after applying different reversal magnetic fields (using VSM), demonstrating that latching on/off ratios of 191:1 (SmCo) and 303:1 (NdFeB) can be achieved. Figure 6b illustrates how the latching force will vary with the distance from the magnet to the ferromagnetic plate.

5. Conclusions
A novel axisymmetric configuration of EPM was proposed. Using simulations and optimization of sub-millimeter axisymmetric EPM it was predicted that the latching force ratio can be tuned from 1 up to 784, for sizes between 8 mm$^3$ and 34 mm$^3$ by varying the thickness of the cap plates. Compared to conventional architectures, the axisymmetric design also provides better performance in a smaller form factor and symmetric magnetic field along the magnetization axis, as opposed to the asymmetric fields in the transverse direction.

A fabrication technique that enables the batch microfabrication of this components was also demonstrated. Two fully assembled EPM SmCo and NdFeB with latching force ratio of 191:1 and 303:1 were demonstrated. Magnoct optical images (MOI) characterization showed the it was possible to cancel the magnetic flux of the EPM cores, applying external reversal fields >300 mT for SmCo or >430 mT for NdFeB. Force characterization using a build on house measuring technique proved that the external reversal fields to turn the EPMs off were >245 mT for SmCo and >282 mT for NdFeB. These are fundamental advances in the small-scale fabrication of EPMs and an important demonstration of the working principle for the axisymmetric EPM design.

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