MAE/ECE 535: Design of Electromechanical Systems
Experimental Demonstration

Project Title: 2D Magnetic Manipulation

YouTube Link: https://youtu.be/VG4nXjl4dR4

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Abstract

For this project, we decided to build an autonomous and manual 2D Magnetic Manipulation device that applies controlled electromagnet fields (via current and voltage limits) to move a magnetic ball (or ferromagnetic object) in a clockwise motion across a planar surface. The device uses four homemade electromagnets with 22 AWG enameled copper wire on ½-in diameter plain steel cores. Each electromagnet has approximately 300 turns and produces a magnetic field that is more than enough to create position-dependent field gradients for motion of the object. Testing of one of our electromagnets shows that the magnetic field produced reaches at least 2900 uT measured at 2 cm and 7 amps, at which point our magnetometer saturates, up to this amperage level at which point the coil begins overheating in a short period of time. This project is relevant to course content on coil magnetic field generation and the electromechanical design tradeoffs.

Introduction

A current carrying-conductor produces a magnetic field that forms closed-loop circles around the wire. The magnetic field strength is proportional with current and inversely proportional with the distance from the conductor. When the conductor is transformed into a loop, the radial components of the magnetic field cancel and produce an axial magnetic field. Extending this to a solenoid with N turns, current (I), length (ℓ), cross-sectional area (a), we know that the on-axis field (assuming a linear and unsaturated core) is :

$$B = \mu * H = \mu * N * I * \frac{\frac{\ell}{2}}{\sqrt{a^2 + (\frac{\ell}{2})^2}} \approx \frac{\mu * N * I}{\ell}, \text{ for } \ell >> a$$

The relationship shows that increasing the magnetic field requires minimizing the magnetic path length and maximizing ampere-turns (NI). The field strength can also be increased by using a ferromagnetic core to increase the permeability:

$$\mu = \mu_0 * \mu_r = \mu_0 * {\sim}3000$$

A magnetic object will experience force with respect to its position (i.e. the field gradient). The object's dipole wants to align with the produced B field and move towards regions of higher field magnitude. For movement of the object, the axial force should be proportional with the gradient:

$$F_x \propto \frac{dB}{dx}$$

The expected limitations for the homemade coils include $P = I^2 * R$ heating losses, non-linear μ_r core saturation, fringing, and non-ideal coil windings with airgaps, which will all lead to disagreement between theoretical and measured values. The model chosen here is very simple as we have many non-idealities, assumptions, and simplifications.

Methods and Materials

The project began with brainstorming and rough calculations for electromagnets that use ½-in plain steel core and 22-AWG Enameled copper wire (with approximately 300 turns).

Phase 1 (Mechanical): We bought materials to construct the mechanical enclosure from Home Depot. The materials included a ½-in plain steel rod, 22 AWG magnet wire, ¼-in diameter 5-in length bolts, ¼-in Nuts, and cardboard. The 3-ft steel rod was cut into ~4-cm cores using an angle grinder and then deburred with a belt/disk grinder. Cardboard circles were then added to the end of each rod core with superglue to assist in the winding process. Each core was then wound with approximately 300 turns(~8 layers with ~37 turns/layer). After winding, the coils were wrapped with saran wrap to prevent unwinding. To validate that a magnetic field was produced by the coils, we drove the coils with a DC power supply at ~4V and 2A and observed the attraction of a magnetic ball to the center of the core from approximately 5cm away. Acrylic sheets were then cut into ~10-cm squares with 3/8th-in holes drilled 1cm away from

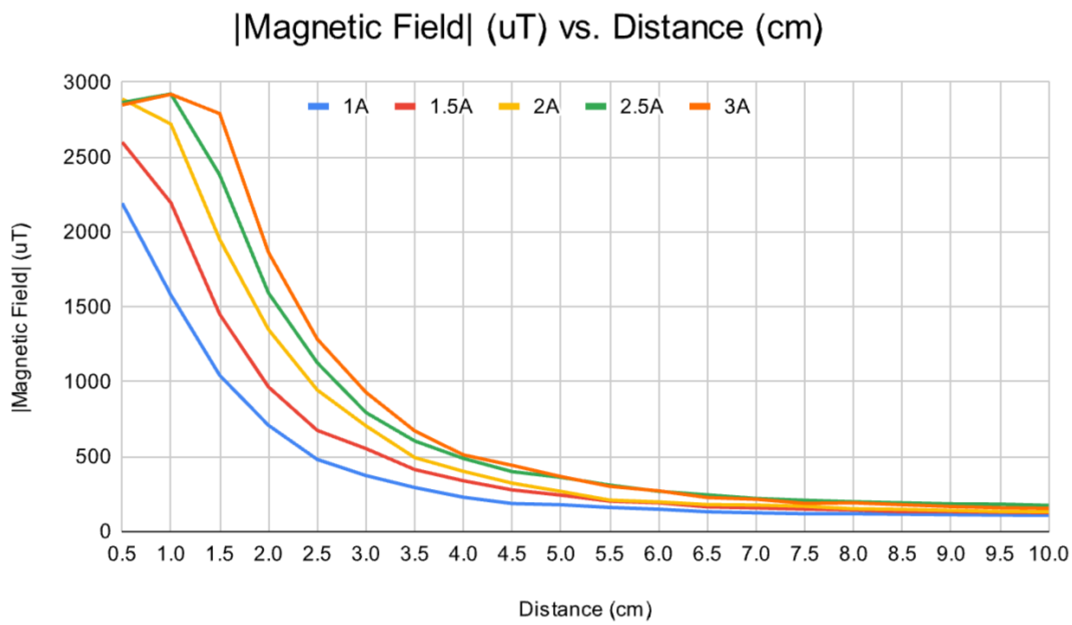
For assembly of the coils, we cut cardboard 1in circles and superglued them onto the ends of the steel cores. Each core was then wrapped with approximately 300 turns of 22 AWG Mag Wire. There were 8 layers with ~37 windings per layer. Each coil was covered with clear saran wrap to prevent unwinding of the coils. Next, we cut the acrylic sheets into three 15mm squares. We marked the corners and drilled four holes in each sheet and fixed the sheets together with the nuts and bolts. We then assembled the platform with 3 layers. The homemade electromagnets were placed on the second level of the platform, which had an adjustable height from the top layer due to the bolt/nut design. Finally, we 3D printed a Jig to hold the four electromagnets in a square like fashion (3.5-cm apart core-to-core) along with four bumpers to prevent the magnet ball from attaching to the ferromagnetic bolts.

Phase 2 (Electronics): We first prototyped the electrical circuitry to drive the four cores autonomously. This includes a 555 Timer, CD4022 Johnson Counter, 4x IRFZ44N N-MOSFETS, 4x 2N2222 NPN Bipolar Junction Transistors, 4x 2N3906 PNP Bipolar Junction Transistors, along with various resistors, capacitors, diodes, and leds. A majority of the electronic components were obtained for free from the ECE makerspace. We first built a manual push-button MOSFET driver circuit for testing the coils. Next, we generated a ~1Hz clock with approximately 50% duty cycle that fed into the CD4022 chip to sequence pulses to the four output coils. Because the CD4022 could not drive the MOSFETs with current limited output pins, we had to include a push-pull BJT stage to adequately drive the gates of the MOSFETS.

Phase 3 (Integration): Finally, we added the timer/counter, gate drivers, and mechanical assembly into one complete device. The distance from the top of the coil to the platform with the magnetic ball was adjustable, allowing us to tune the field strength at the top plane. The final system reliably moved the magnetic ball autonomously in a clockwise pattern. Documentation of the build process is in the attached YouTube video.

Phase 4 (Coil Characterization): To characterize our electromagnets' field intensity at different distances and current values, we placed a coil at a fixed position on a piece of paper with markers delimiting 0.5cm increments. Then, using an app that gives the values of an iPhones raw magnetometer values x,y,z we measured the magnetic field intensity in micro tesla (uT) with the axis perpendicular to the coil windings, (right hand rule). Measurers were made from 0.5cm to 10cm, at the current levels of 1.0A, 1.5A, 2A, 2.5A, 3.0A.

Results



Measurements very close to the coil experienced noticeable position deviations as the iPhone (magnetometer) seemed to be saturated. Experimental results differ over a magnitude with what is obtained from simple theoretical calculations (it is unable to accurately model the realistic geometry of our coil). FEA could assist in obtaining more accurate theoretical results. An interesting observation was that at the higher current levels the magnetic field intensity seemed to have a small increase from 0.5 cm to 1.0cm before dropping off, possibly due to the placement and geometries of the magnetometer with respect to the coil. An empirical fit with the 1A data can be seen in our project video.

Conclusions

Overall, we are quite satisfied with the results we achieved. There we a lot of challenges and unknowns we faced throughout the project's development, mostly in the things that seem simple (like drilling holes in acrylic). Opting for a more hands-on approach where we made our own coils from scratch, creating a timing circuit from discrete components instead of using a microcontroller, and making our own enclosure, allowed us to more intimately face all the design variables that exist when designing an electromagnet application. Very early on in the project we realized that for this sort of application we had to throw rigorous calculations out of the window, deviations in core geometry, winding, support structure material, circuit layout, timing, coil placement, etc. All can have compounding effects that make it nearly impossible to make any accurate calculations (without online tools), especially when many of these variables can change at the same time. We realized it was best to utilize the concepts, not the formulas. Iterating, and optimizing was much more efficient this way, and is what allowed us to achieve a working device in the end.