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Laboratory Model of Magnetic Frictionless Flywheel and Hoverboard

Angel J. Gutarra-leon

Northern Virginia Community College, ajg269@email.vccs.edu

Vincent Cordrey

Northern Virginia Community College, vlc268@email.vccs.edu

Walerian Majewski

Northern Virginia Community College, walerus@aol.com

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Laboratory Model of Magnetic Frictionless Flywheel and Hoverboard

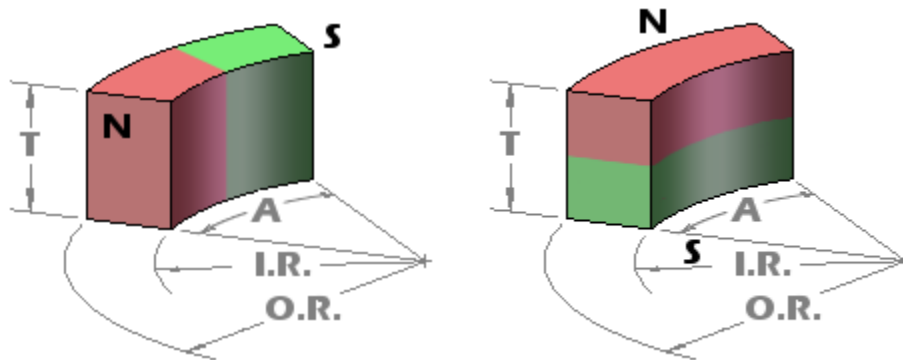
Introduction

The circular Halbach array is composed of twelve NdBeB grade 52 arc-segment magnets with magnetizations alternating between axial and circumferential (Halbach, 1985). The segments are arranged into a series of three Halbach arrays so as to amplify the field on one face of the wheel and weaken the field on the other face. This wheel, with the strong field facing up, was spun under a series of ring assemblies of inductive copper coils to produce a lift and a drag (or torque) force on the suspended coil array. It is expected that the force of repulsion upward will be strong enough to overcome gravity if the two pieces' relative velocities are high enough (R.F. Post, D.D. Ryutov, 2000).

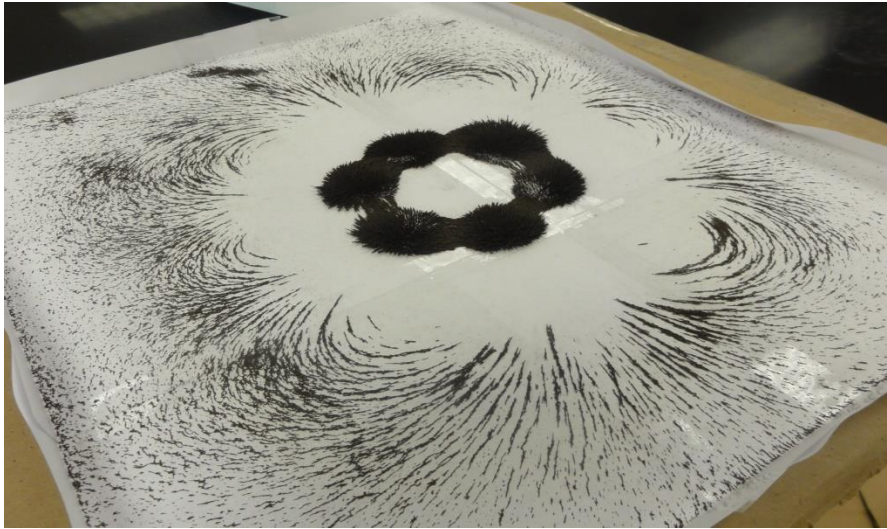
Construction of the Magnetic Wheel

First ten of these 12 magnets were inserted by hand into a circular housing of aluminum and were held in place with set-screws around the inner and outer ring. The final two were positioned using a half ton press, because during assembly we discovered that the forces and torques created by magnetic repulsion/attraction of NdBeB magnets were too strong to be manipulated by hand, and that the magnets are brittle.

Circumferentially and axially magnetized magnet segments, with internal radius 1", external 2", central angle 30 deg.

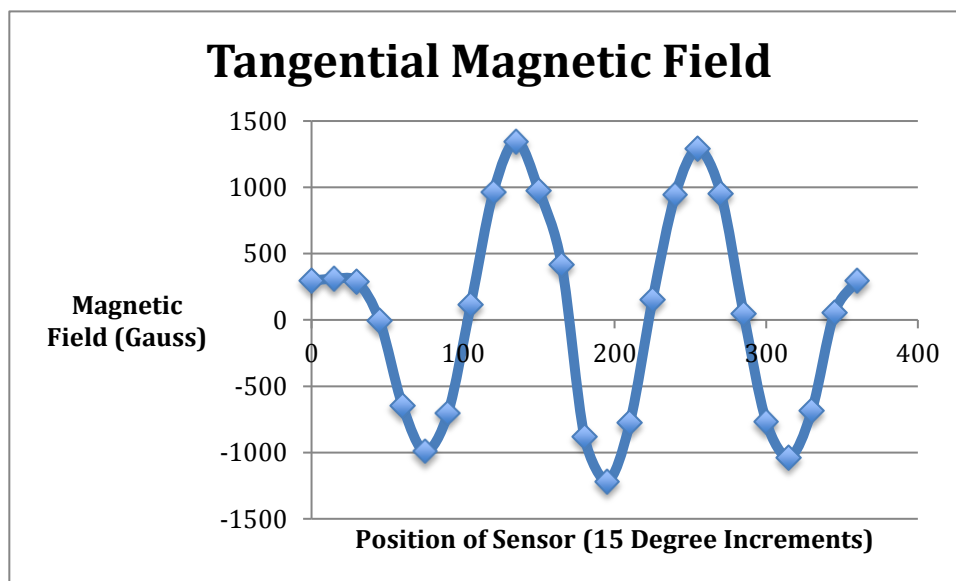
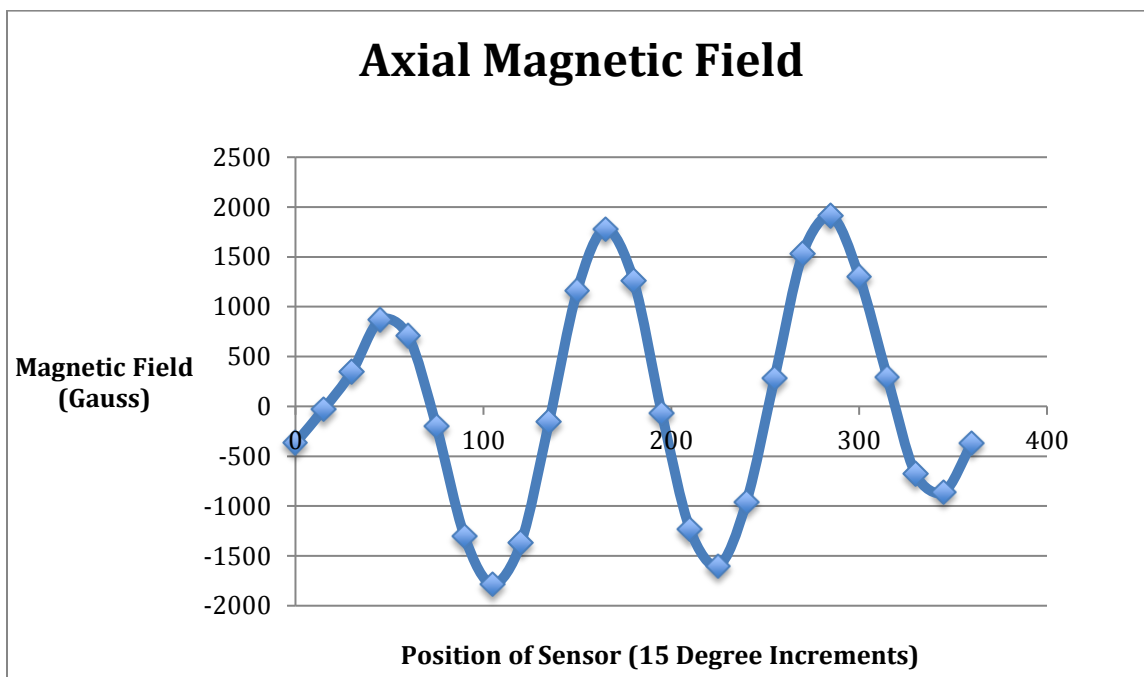


The inner radius of the array was 1 inch, and the outer radius was 2 inches, weight 18.4 N. The field is enhanced on the top side. Our field is not sinusoidal, because shunt magnetizations are not circumferential, but only perpendicular to the radial direction of the middle of each segment.



Measuring the Magnetic Field

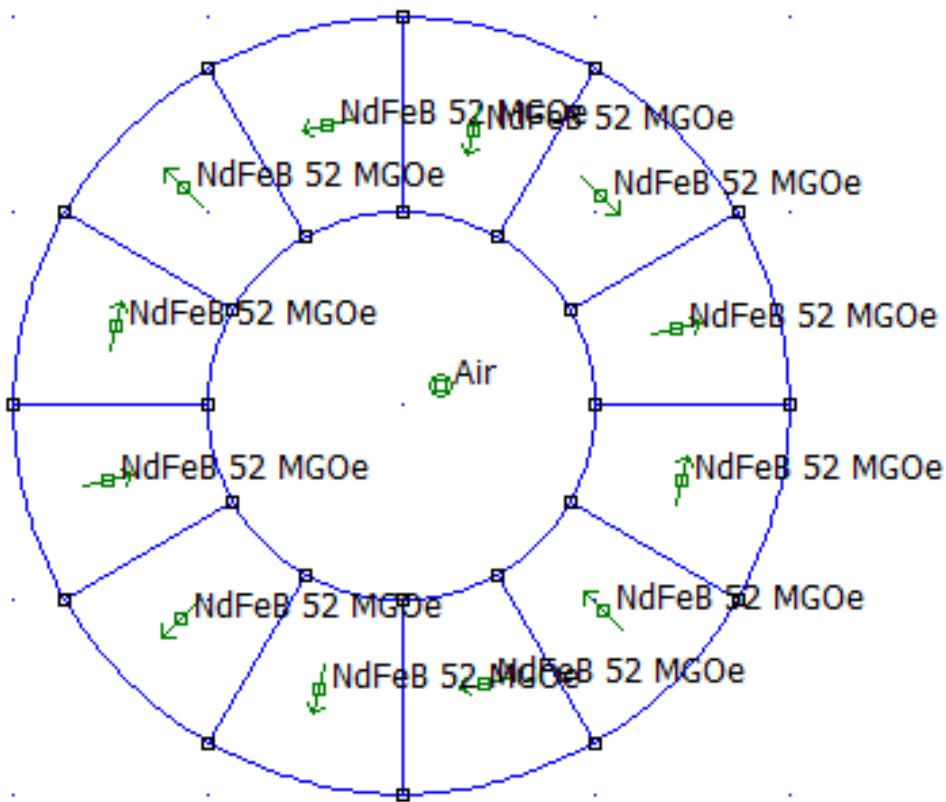
A magnetic probe was used to measure the tangential and the axial magnetic field of the strong side of the Halbach Array. We held the probe at a fixed distance and from the center of the wheel and then we turned the wheel in 15 degree increments to measure the magnetic field. For the axial measurements, we held the probe 4.2cm from the center of the wheel, specifically 4cm from the center of the wheel traveling horizontally, then 1.435cm above the magnets. Similarly, to measure the tangential field, the probe was placed 4.3cm from the center of the wheel, specifically 4cm from the center of the wheel travelling horizontally and then, raising the probe 1.575cm above the magnet. The three peaks and valleys per revolution tell us the magnet field is flipping from north to south just as a Halbach Array should be (Halbach, 1985). However, the magnetic field has a very noticeable irregularity in that not all peaks and valleys are the same height and in particular one cycle of north-to-south rotation of the magnet has a much lower magnetic field strength than the others. We suspected that one of the shunt magnets must be improperly aligned.

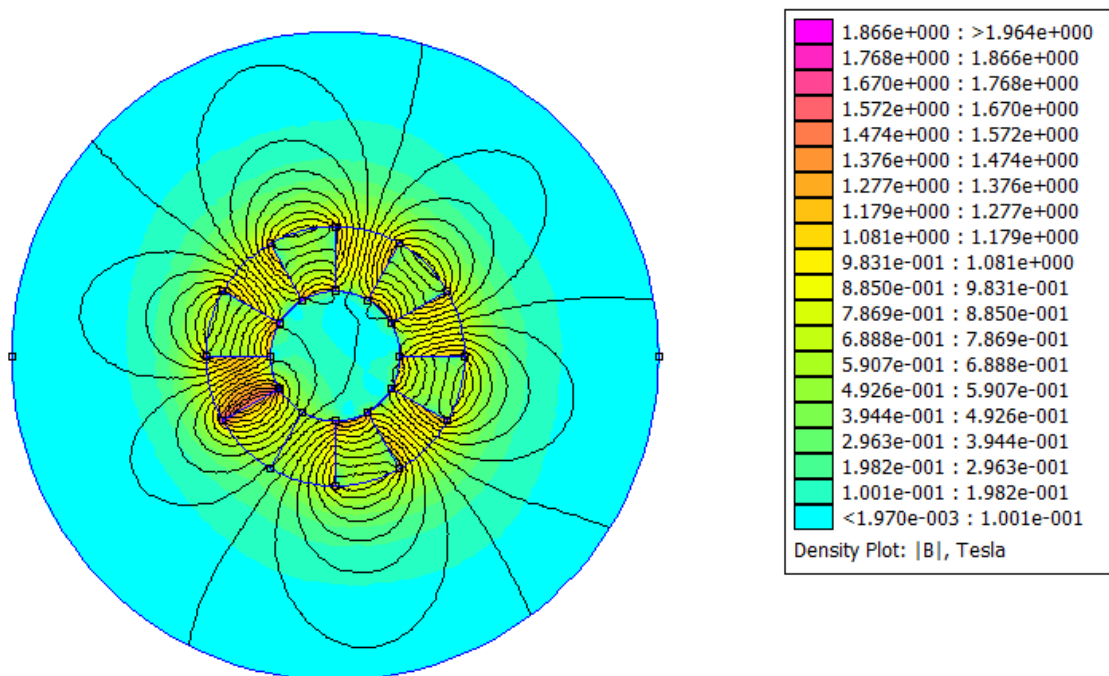


Modeling the Magnetic Field

This is a model of the magnetic field using a software called Finite Element Method Magnets. The software only works in two dimensions. Therefore, the model of

the Halbach Array is changed into two-dimensional space. In the model, the strong side of the Halbach Array extends outward radially from the wheel and the weaker side of the Halbach Array is aiming towards the center. When all the magnets are aligned properly there is a very strong symmetrical magnetic field on the outside and a very weak magnetic field on the inside. However, if one of the shunt magnets is turned 90 degrees so that north side of the magnet is now facing radially outwards the magnetic field now has irregularities in the outside and inside the wheel. The magnetic field produced by this model matches up with what is shown in the graph. Therefore, one of the shunt magnets must have been misaligned when it was constructed.





Inductive Coil Array

One coil array (on left below) consisted of five 18-gauge copper wire coils of approximately two hundred turns and having an outer diameter of 1.25", an inner diameter of 0.75" and a height of 1.00", with the inductivity $L=100$ mH, resistance $R = 1.0$ Ohm, secured to a non-magnetic, non-conducting (Masonite) board every 72 degrees. They created a toroidal sequence of separated shorted solenoids.

Another identical coil array was constructed with one slight modification. The non-conducting (Masonite) board was replaced by a 13cm radius aluminum disk, to be used as the rotating inductor.

A third coil array (on right below) was composed of 10 shorted coils made from 18-gauge wire. Five of the coils were 1.25 inches in diameter and 1 inch in length, with an inductance of 4 mH and a resistance of 1.0 Ohm. The other five coils were 1 inch in

diameter and 1 inch in length, with an inductance 3 mH and a resistance of 0.75 Ohms.

The coils were evenly spaced, alternating large and small, around a 6-inch diameter piece of 1/8" Masonite hardboard, a spacer made from 3/4" nominal PVC pipe. Their mutual inductance has not been estimated. They became warm in operation.

Different designs of inductor ring on non-magnetic, non-conducting or conducting bases:



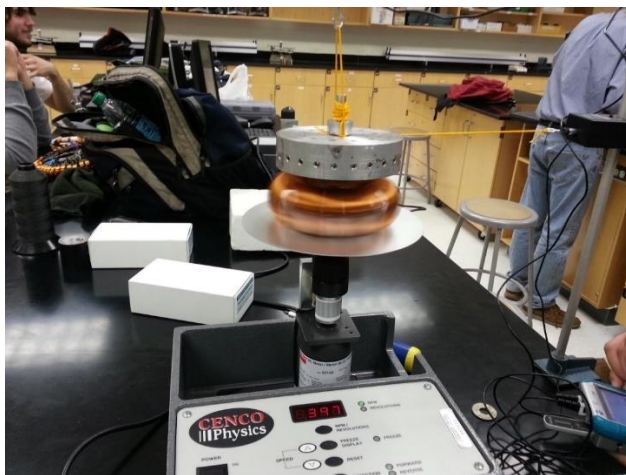
Forces were measured using Vernier Dual-Range Force sensors. A rotator with an RPM reading was used to create a relative angular velocity, by rotating either the coils (set on an aluminum disk) or the magnet. The rotator and coil system became unstable at the high rotational velocities. This lack of stability may have been increased due to an imbalance of the magnets spun with the rotator. Without the magnets attached, the rotator was capable of spinning at 4,000 rpm, but when the complete system is set up, 1,500 rpm seems to be the maximum speed we were able to achieve. The distance between the inductors and Halbach array influences the magnitudes of the lift and drag force. If the

magnitude of the drag force is large enough, the rotator motor becomes overloaded and shuts off.

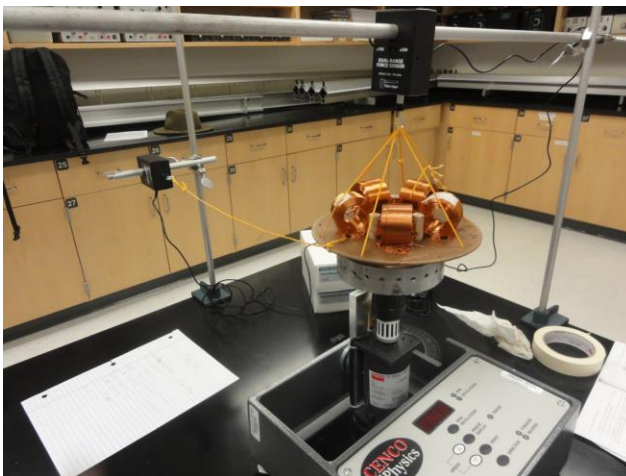
Two Versions of the Experiment

1. Ring of inductor coils set on aluminum plate rotating below suspended circular

Halbach magnet:



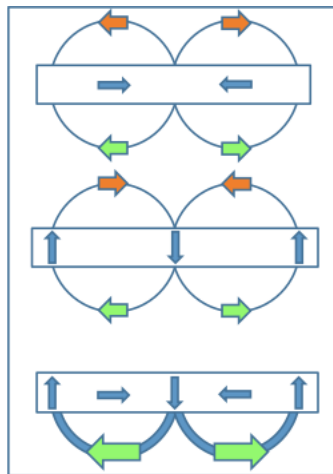
2. Inductor ring suspended on a force sensor, second sensor measures the drag, rotating magnet on rotator:



The coil array was suspended from three force gauges, whose output values were added to obtain the apparent weight of the coil array. The “drag” force calculated in the theoretical predictions for linear motion is here exerted as a torque on the coil array, represented as the tension force at the sensor, applied at the rim of the plate.

Basic Theory of a Halbach Magnet and Its Motion with Respect to an Inductive Track

How the one-sided flux is created: magnetization of each next magnet is rotated by 90 degrees. When field from the horizontal magnetic dipoles (a) is added to the field from the vertically magnetized dipoles (b), the resulting field (c) is one-sided.

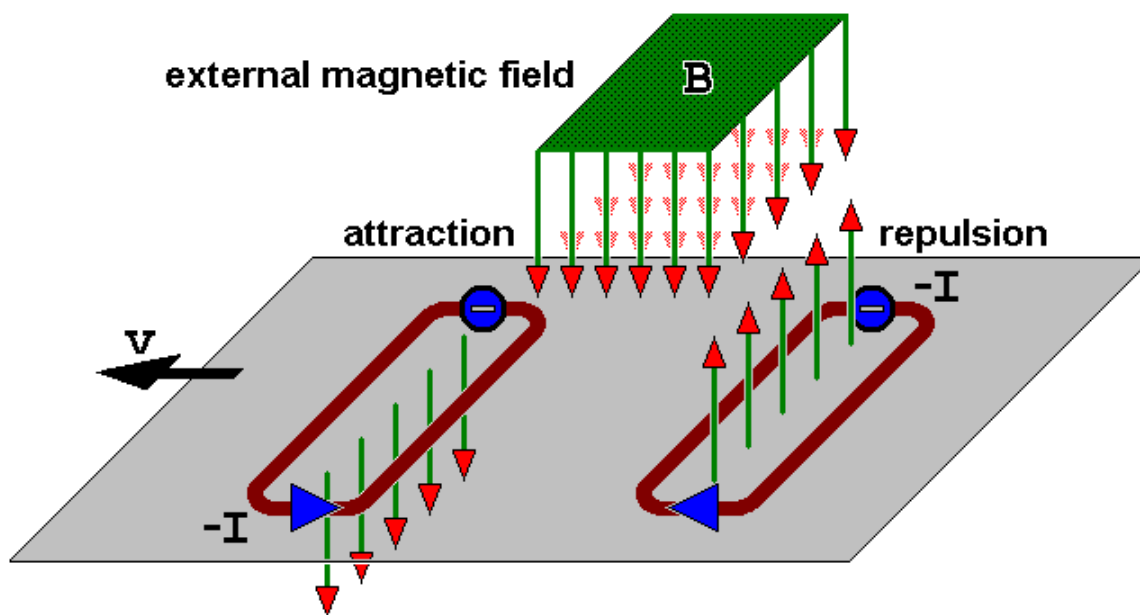


If we repeat this pattern with more magnets while joining the magnets at an angle the result would be a circular Halbach Array.

Basic Inductrack Equations

Moving a system of coils with respect to the Halbach magnet will produce in them instantaneous induced voltages, and so currents, in such directions that their magnetic fields will be on average repelling the moving magnet, plus exerting a magnetic drag on it, both as the results of the Faraday Lenz laws (Halbach, 1985). Eddy currents behind the moving magnet on the diagram below exert attraction – magnetic drag, and in front of it – levitating repulsion (arrows indicate directions of flow of electrons, given by $-I$ – opposite to the conventional current directions).

This relative motion near a magnet causes any conductor to behave like a diamagnet – to repel, instead of to attract ferromagnets. Investigating this effect requires using non-ferromagnetic conductive materials like aluminum or copper, as the ferromagnetic ones are also strongly attracted to our Nd magnet.



“Eddy Current” (2016)

Induction EMF from the relative motion is given by the Faraday's Law:

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

In the simplest case, when flux = BA:

$$d(BA)/dt = A dB/dt = A(dB/ds)(ds/dt) = vA(dB/ds),$$

v =relative speed of the coil and magnet , A area of coil, B field of magnet, dB/ds = variation of the field in the direction of motion, provided, with sudden field reversals, by the Halbach magnet.

Induced voltage in each coil of resistance R and inductance L from variable vertical magnetic flux of amplitude Φ_0 in relative motion with velocity v enters the circuit equation:

$$\varepsilon = L dI/dt + RI = \omega \Phi_0 \cos \omega t$$

Rotating field's oscillation frequency

$$\omega = (2\pi/\lambda)v,$$

λ is the space period of the magnet.

Application to circular motion

Here

$$v = \Omega r$$

is the linear speed of magnets, Ω is their rotational velocity, and

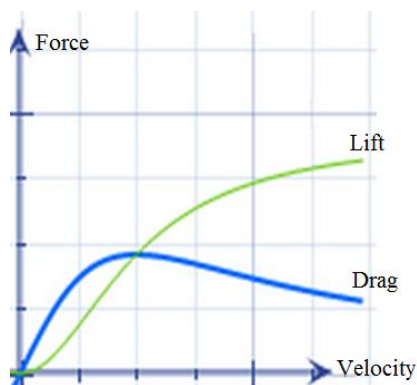
$$\omega = (2\pi/\lambda)v = (2\pi/\lambda) \Omega r = (2\pi r/\lambda)\Omega = N\Omega = 3\Omega$$

in our case with $\lambda = 4''$, $r=2''$. N is the number of Halbach 4-magnet periods fitting around

the circular Halbach magnet.

Main theoretical results (Post, 2000) for average lift and drag forces: for large velocities the lift monotonically increases to a constant limit, drag eventually decreases to zero, and their ratio is given by:

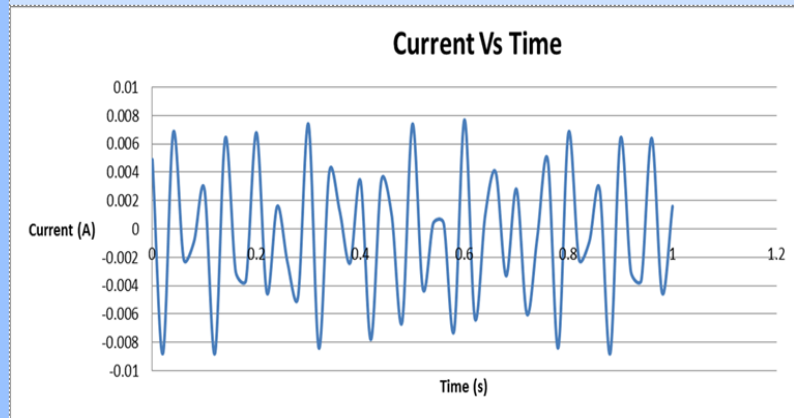
$$\text{lift/drag} = (L/R)N\Omega.$$



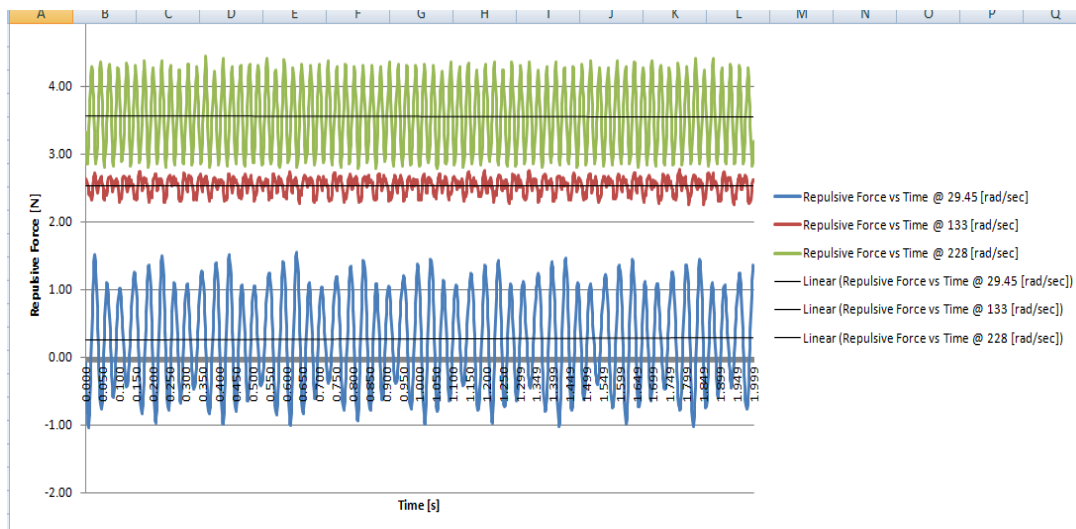
Experimental Results

We measured forces in the interval $2.5 < \Omega < 25$ rad/s (up to 250 rpm, after which the rotator destabilized), which corresponds to $0.25 < v < 2.5$ m/s for the speed of magnets. Our 12-segment ring – is an approximate dodecapole Halbach magnet (magnetizations of shunt magnets are not strictly circumferential, only perpendicular to radial lines).

The current running through one of the coils in the array was recorded at several rotational velocities. Interestingly, the current does not fluctuate in a sinusoidal fashion, implying that the magnetic flux passing through the coils does not vary in a sinusoidal fashion either. Below is a graph of current fluctuation in the duration of one second:

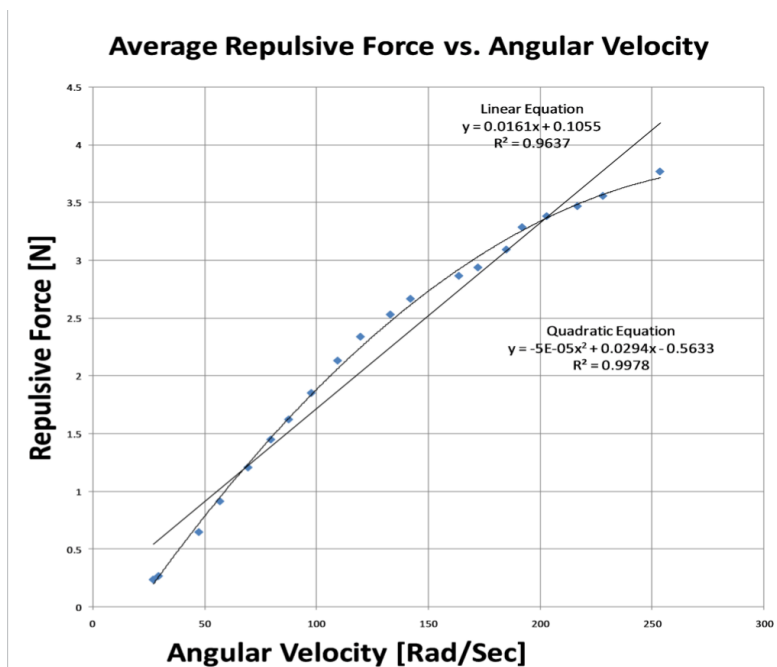
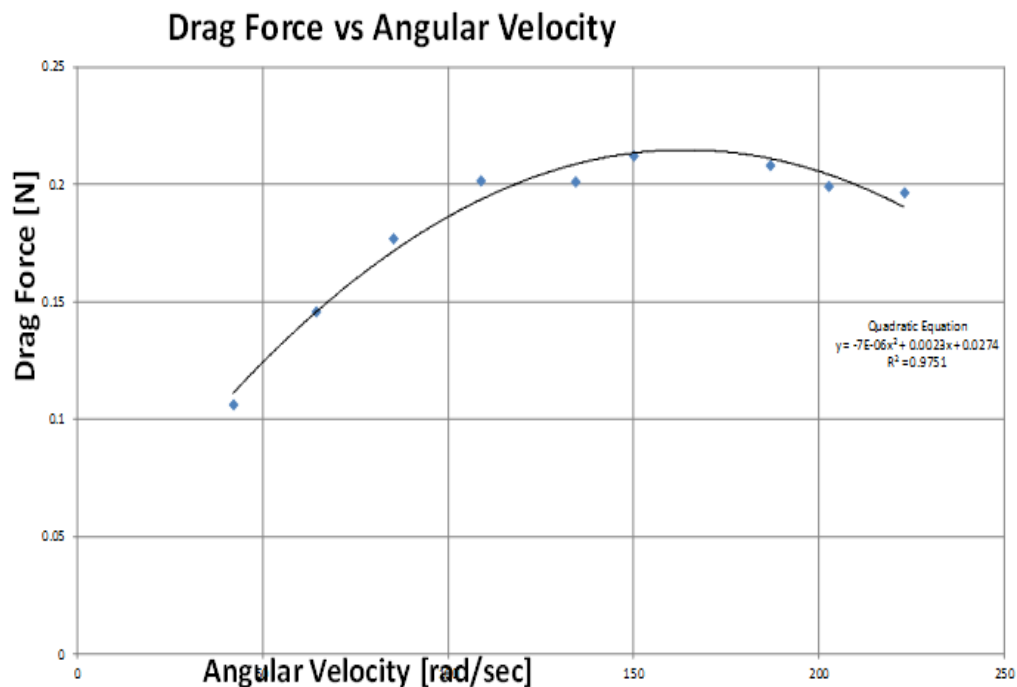


Time dependence of the oscillating lifting force acting on the inductors at several rotation speeds.

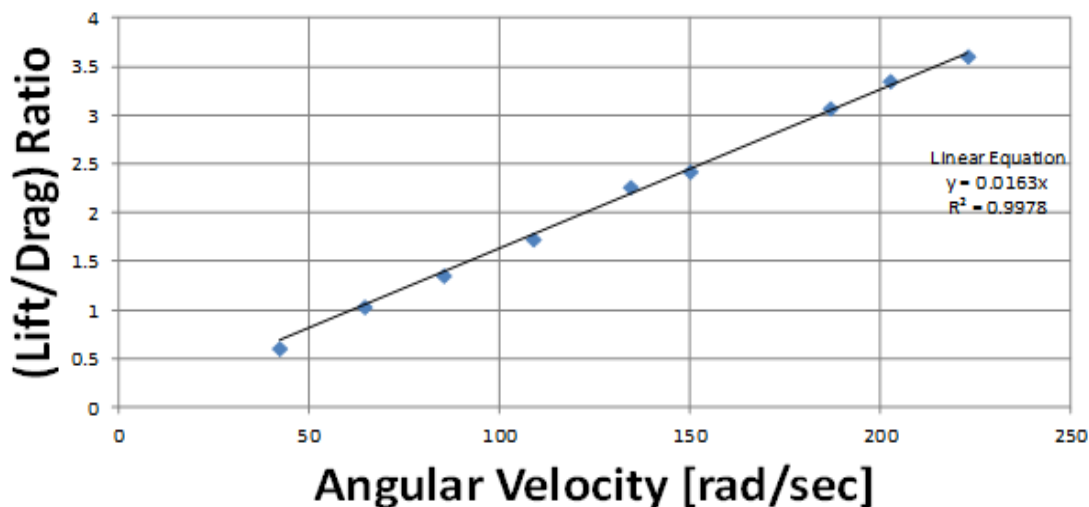


Experiment 1

Repulsive (lift) average induction force on inductors from rotating Halbach magnet:

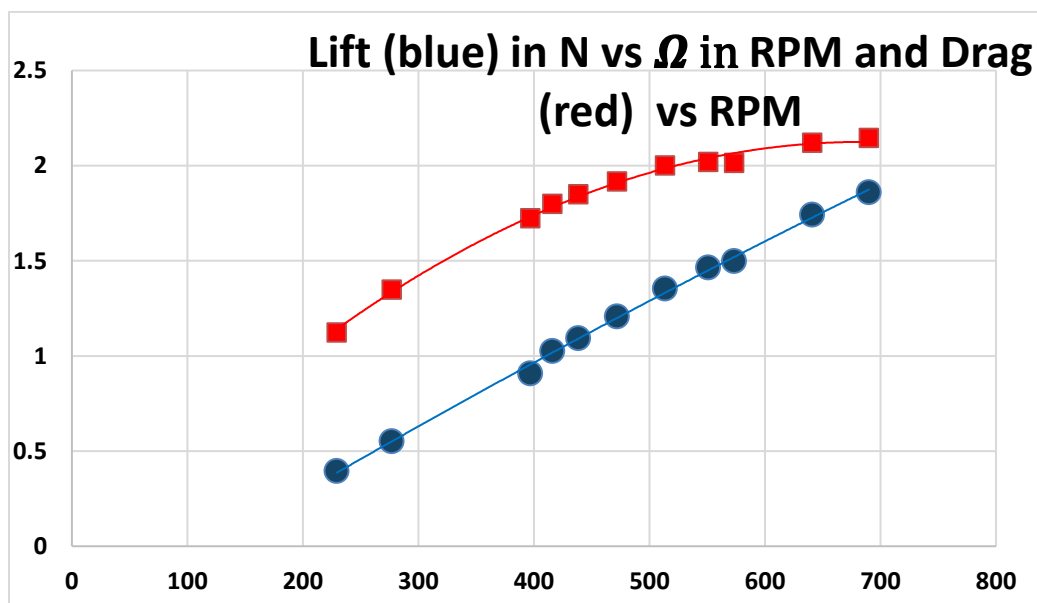


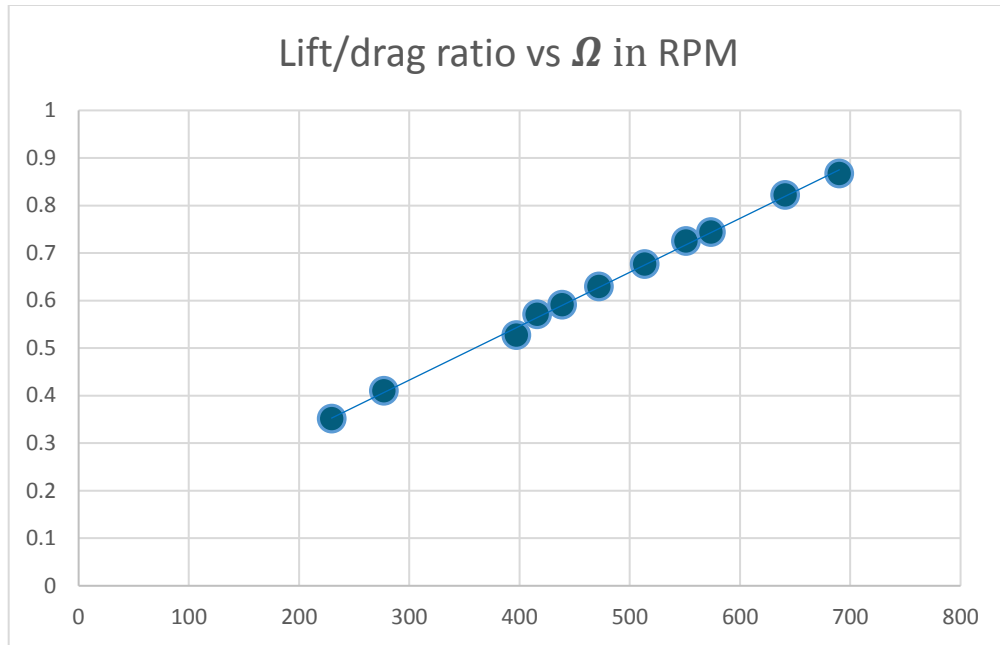
(Lift/Drag) Ratio vs Angular Velocity



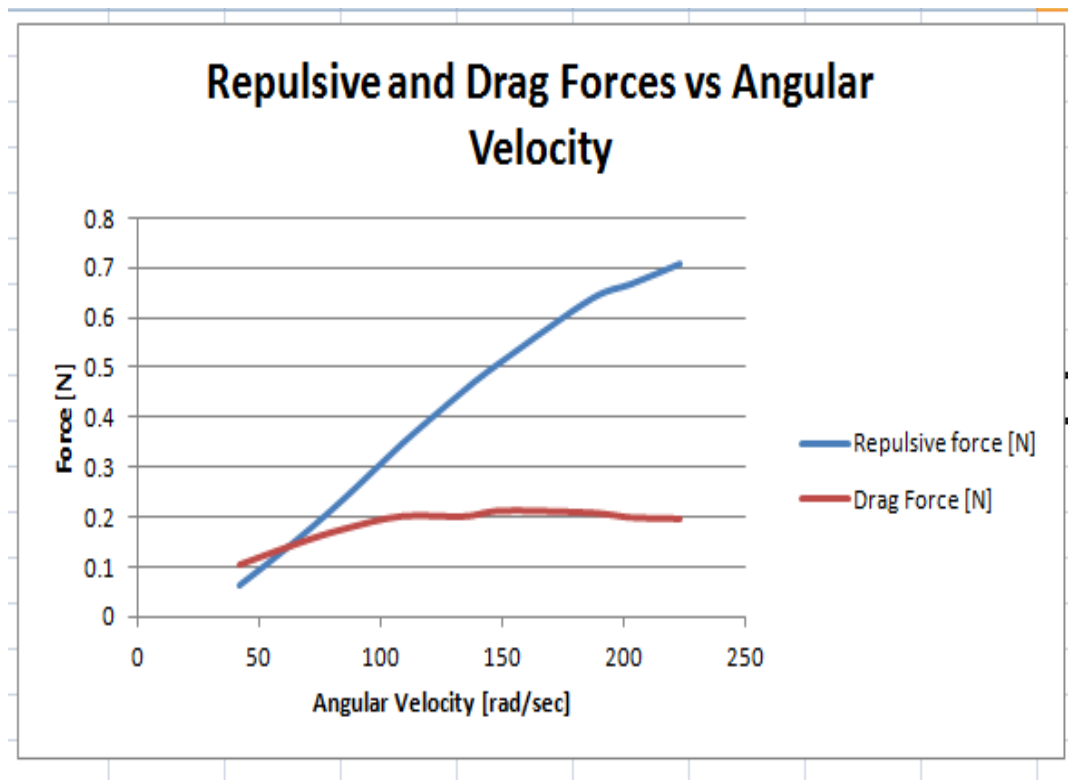
$$L/R = 100 \text{ mH}/1 \text{ Ohm} = 0.10 \text{ s},$$

Experiment 2



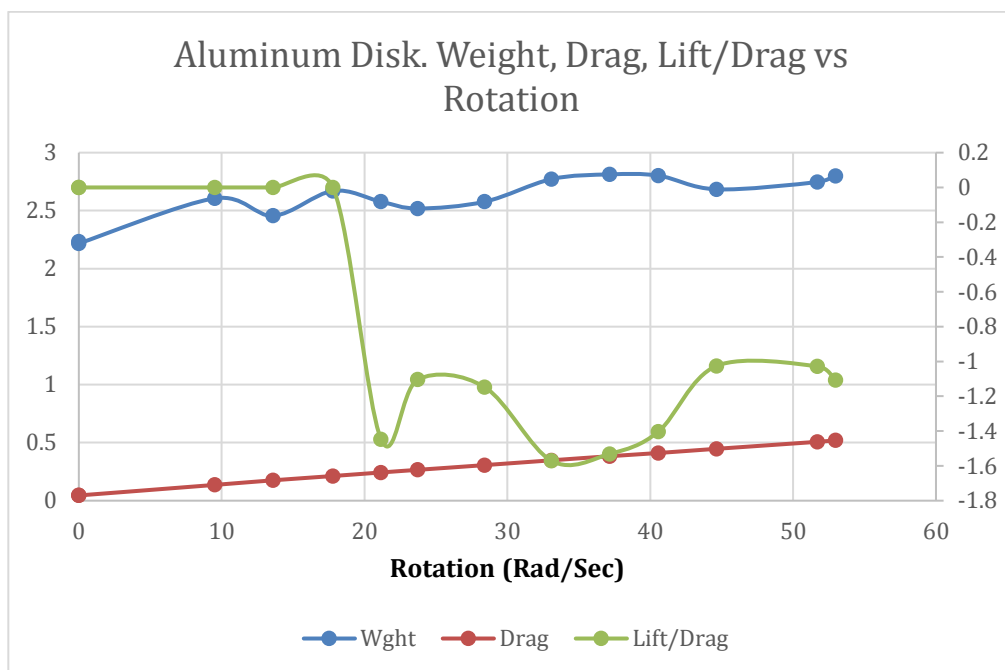


Experiment 3



Experiment 4

(demonstrating the instability of levitation of the the solid aluminum disc)



During this experiment there was aluminum disk would swing like a pendulum. As a result no levitation was produced, but instead there was a weight increase. The swinging of the disc might be caused by the fact that the magnetic field is not as uniform as it should because of the misaligned shunt magnet. In the future that magnet will be fixed and a new suspension method for the aluminum disc will be built and designed.

Conclusion

In agreement with the Inductrack formulas as applied here to a circular Halbach magnet rotating below the inductor ring, we are able to confirm the increase of the average lifting force and of the lift/drag ratio, and decrease – after some point - of the

drag force and of the amplitude of the force oscillations, with increasing speeds of rotation up to 2500 rpm. The linearity of the lift/drag ration and its slope being equal to L/R is approximately confirmed, too.

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