A Procedure for Analyzing A Magnetic Levitation Toy

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Low-cost toys have been shown to provide useful test beds for facilitating student learning. In electromagnetic theory, inexpensive repulsive magnetic levitation toys can be used to introduce students to electrostatics. To this point, this paper presents an in-depth analysis for the Fascinations Levitron Revolution repulsive magnet toy. The purpose of this analysis was to develop a method for reliably testing and measuring system characteristics. A deconstruction of the device allowed for accurate measures of geometry, electric current, and magnetic field. Several methods of analysis, including first principle derivation and system measurements were applied to gauge and verify system characteristics. The individual magnetic fields were investigated to determine the forces responsible for stabilizing and levitating the magnet. This paper presents the results of this analysis and details of the methods used so that these procedures can be extended to other undergraduate engineering settings.

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Introduction

The Fascinations Levitron Revolution is a device in which a permanent disk magnet of 80-g is levitated in air above the unit at 0.019m. The manufacturer describes the auto correcting as 'EZ float technology' to keep the object in equilibrium. The Levitron can sustain the addition of approximately 12 ounces of weight.

This device originates from the original Levitron device, where a permanent magnet and the inertia from a spinning top can levitate the top in mid-air above the base. The key part to this original design was the angular momentum responsible for stabilizing the levitating object. For the new design, the spinning top was no longer needed as a new stabilizing method was implemented [1]. Different than the original, the Fascinations Levitron device uses the combination of permanent and solenoid magnetic fields to levitate a magnetic disk above the surface. Adjusting the current supplied to the solenoid in order to alter its magnetic field strength allows the disk magnet to sustain equilibrium.

According to Earnshaw's theorem of 1842 [2], magnetic levitation is not possible for static magnetic dipoles, therefore hindering the use of only permanent magnets to levitate an object in equilibrium. This phenomenon can be explained by magnetic moments, which determine how much torque is applied when an external magnetic field is present. While stationary and not spinning, the levitating magnet falls out of equilibrium easily due to small deviations from a balanced state, making the slight imbalance greater until the magnet falls out of equilibrium.

Earnshaw's theorem is applied to all non-moving ferromagnetic materials; however, there are instances when this theory does not apply due to the type of magnets used. Exceptions to Earnshaw's theorem include rotation, feedback systems and oscillations.

The limitation of the original Levitron was due to slight imbalances that escalated due to magnetic moments, which was solved by adding spin to the top. For the new Fascinations Levitron, Earnshaw's theorem did not apply due to the addition of current induced magnetic fields. The combined system of permanent and current induced magnetic fields allow the system to self-stabilize and correct for slight imbalances without having to spin.

This paper describes the analysis and practical measurements of the Fascinations Levitron Revolution toy to discover how it levitates a disk magnet and the forces exerted from the permanent magnet, solenoids, and levitating disk magnet. The method applied in this work can be useful in other magnetic field measurement applications as it was done in person and no unobtainable expensive tools or equipment was used.

Theory

Magnetic fields are the result of electric current and are specified by direction and magnitude. These fields can be produced by electric charge currents moving through wires and from objects made of magnetized ferromagnetic materials. Magnetic fields produced by electrons are dependent on the particle's charge, velocity, and acceleration. When point charges move through a cylindrical wire, magnetic field lines are formed concentrically around the length of the wire. These concentric circles are strongest close to the wire and decrease in strength as the distance from the wire increases. The direction of the field around the wire is determined by the "right hand rule," where the right hand is held above the wire with the thumb pointing in the direction of the current. The direction of the fingers wrapping around the wire describes the direction of the magnetic field produced.

The magnetic field produced by a steady current can be calculated using the Biot-Savart Law,

$$B = \frac{\mu}{4\pi} \int_C \frac{Idl \times r'}{|r'|^3} \ . \qquad (1)$$

This law uses magnitude, direction, length, and proximity of the electric current to determine the magnetic field at a specific point.

A. Permanent magnets

A permanent magnet is a ferromagnetic material that constantly produces a uniform magnetic field. A permanent magnet is capable of both producing its own magnetic field and responding to external magnetic fields. The magnetic field produced is proportional to its magnetic moment.

B. Solenoids

To generate a nearly uniform magnetic field, a current carrying wire can be coil wound into a tightly packed helix. This shape, known as a solenoid, can be wrapped around a metallic core to help produce a uniform magnetic field by directing the field lines through the center of the coil.

This uniform field can be used similar to that of a bar magnet but the geometry and current applied can be modified to produce different magnetic field values based on current needs. The magnetic permeability of the material, number of turns, and length are used to calculate the resulting magnitude of the field as seen in Figure 1. Applying Ampere's Law to a rectangular path about the solenoid allows the current to be a factor in the equation to solve for the magnetic field. The magnetic field strength is directly proportional to the amount of the current flowing through the solenoid as seen by the solenoid magnetic field equation,

$$B = \mu \frac{N}{L} I. \qquad (2)$$

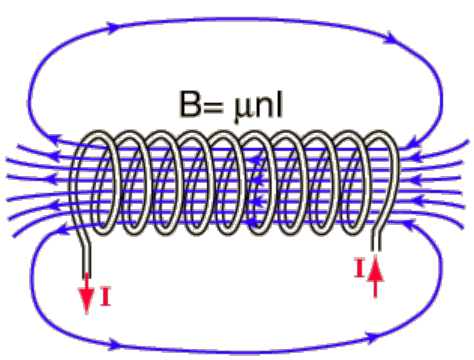

Figure 1: Magnetic field of a solenoid. μ = magnetic permeability. N = turns. L = length of solenoid.

The construction of a solenoid consists of an insulated wire wrapped around a central core. However, the magnetic field is only induced when an electric current is flowing through the wire. With the current flowing, the magnetic field lines of the solenoid closely resemble that of a permanent magnet.

C. Gauss Meter Analysis

A Gauss meter measures the strength of nearby magnetic fields. Allegro Microsystems A1302 Ratiometric Linear Hall Effect sensor is an integrated circuit (IC) optimized to produce a voltage output proportional to an applied magnetic field [3]. To use the A1302 as a functional gauss meter, a supply voltage of five volts must first be connected to the V_{CC} and ground. By probing the V_{OUT} and ground terminals using a digital multi-meter (DMM) when no magnetic field is applied, the meter will read a value that is half the source voltage. The sensitivity, k, for the A1302 is 1.3 mV/G. The field strength proportional to the voltage can be calculated using equation 3,

$$B = \frac{(v_1 - v_0)}{k} \qquad (3)$$

where v_0 is half of the supply voltage and v_1 is the output voltage. In order to record the value of the magnetic field perform the calculation internally.

Two 330-Ohm resistors in parallel with the V_{CC} and ground allow the voltage between the resistor and V_{OUT} to be read as zero volts when probed. Using the sensitivity value of the Hall sensor, the DMM output was reduced by 76.9% to read 1V = 1000 Gauss (0.1 T) for real-time understanding of the measurements. The max field can be measured at ± 2.5v = ± 2500 Gauss.

To implement this ratio into the circuit, the voltage division equation was used to determine the resistance required to modify the output value [4]. In the circuit, the fraction of resistors to equivalent resistance needed to match the 76.9% percentage of voltage output to sensitivity. Two resistors that can be used for this ratio to be implemented are a 14k and 47k resistor as seen in the circuit diagram in Figure 2. With these resistors added to the circuit, the output voltage is calculated at 77%. Compared to the needed value of 76.9%, this 77% value will suit the needs of this experiment as 0.13% error in output readings did not change the purpose or results of this experiment.

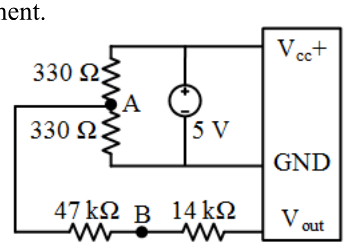

Figure 2: Circuit design of a hall sensor with relative output readings across node A and B.

Methods and Analysis

To perform an analysis on the magnetic field attributes associated with the Levitron Revolution, we used the Gauss meter and amp-meter to measure the magnetic fields of each component during active and inactive operation. In order to measure the magnetic fields by amp-meter, the toy needed to be disassembled to give access to the solenoid wires and to measure solenoid geometry needed for the equation that relates current to magnetic field (dissembled part seen in Figure 2). The solenoid geometry was measured as shown in Figure 4 and is displayed in Table 1. To ensure the accuracy of these magnetic field measurements, multiple methods were used at each step to check the results. The magnetic fields generated were measured first by an amp-meter between adjacent solenoids and second by a Gauss meter. For the second experimental approach, two different Gauss meters were used, one built as shown in Figure 2 and one store bought to check the accuracy of the created Gauss meter.

The first method for measuring the fields generated by the solenoids was using an amp-meter to directly measure the current through the solenoids during different states of operation. The amp-meter was placed in series between two of the diagonally adjacent solenoids. The device was then powered on and the magnet was placed in position where it would remain stable during normal operating conditions. After bridging the terminals from the removed pair of solenoids to complete the circuit, the current across the solenoid was measured to be in the range of 0.50 and 0.60 Amps, thus setting a basis current to work with. The experimental setup is seen in Figure 5.

This range was not accurate enough to use for further analysis, so another experimental technique was used. The combination of the Gauss meter built as described in the theory section, and a HT20 Tesla meter, was used to ensure that the two devices obtained the same measurements.

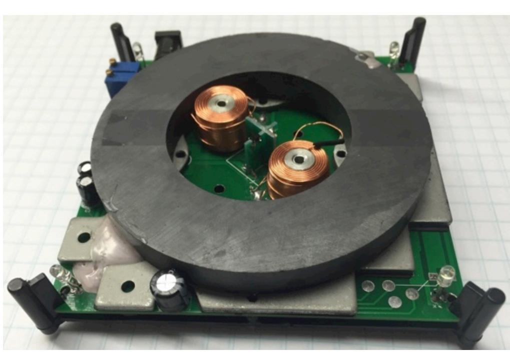

Figure 3: Layout of Levitron magnetic base and solenoids.

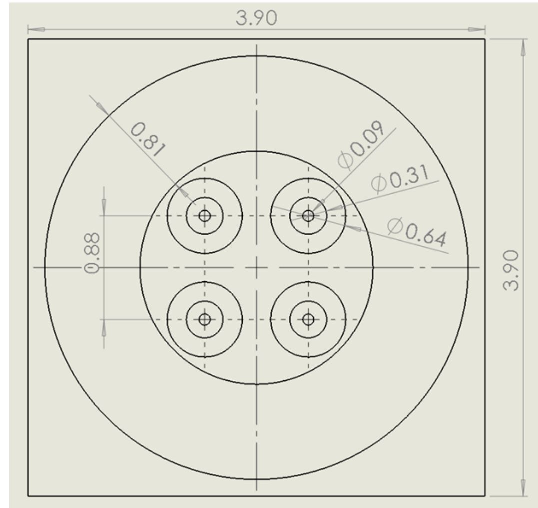

Figure 4: Measurements of the magnetic base and the geometry of the solenoids.

Table 1: Insulated Copper wire measurements per solenoid.

Diameter (mm)	0.36
Total Length (meters)	15.11
Inner Diameter (mm)	7.95
Outer Diameter (mm)	16.25
Height (mm)	12.01
Number of Turns	400

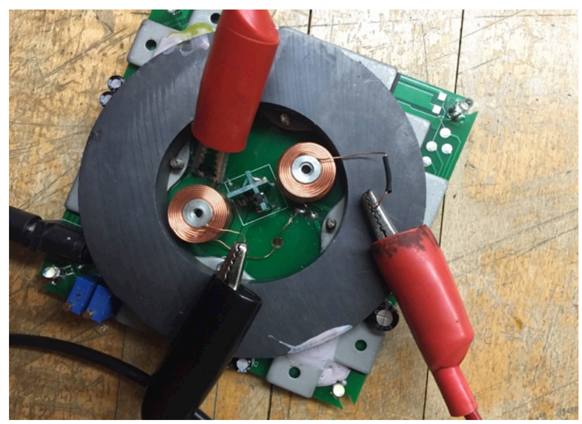

Figure 5: Measuring the current through the solenoid using the second method.

Some basis measurements found during disassembly and analysis showed that a total of four solenoids have been used in the Levitron Revolution to help sustain equilibrium. The solenoids are separated a distance of 22.44mm and are connected diagonally in series, as shown in figure 4.

For the second approach, to find the amount of magnetic force generated by the solenoids, the Gauss meters were used to obtain multiple field readings during different operational states in the system. All measurements for this approach were taken at Z_0 on top of plate to assure accurate field readings. The first measurement was taken when the device was powered off and no magnets were generating a field other than the permanent toroidal magnet inside the device. This value was found to be 48.1mT south.

The disk magnet, which typically sits in equilibrium during normal operation, was isolated and the magnetic field was measured at a position relative to z=0. This value was found to be 27 mT north. The last measurement taken was the total field strength during normal operating conditions. This force was a measurement of the combined field from both permanent magnets and the solenoid coils. The value for this measurement was found to be 1.5mT north by using

$$B_{Toroidal} + B_{Disk} + B_{Solenoid} = B_{Total} \quad (4)$$

with the parameters found in Table 2.

Table 2: Parameters for equation 6.

B_{Total} (mT)	1.5 North
$B_{Toroidal}$ (mT)	48.1 South
B_{Disk} (mT)	25 North

According to the laws of equilibrium and electromagnetics, summation of forces along the vertical z-axis sum must be zero for equilibrium to be achieved in a system [8]. The magnetic field generated by the solenoid was found to be 22.6mT North.

To confirm the validity of this result, using the known parameters in the Biot-Savart Law Equation [1] and the field strength of each solenoid, the current was found to be 0.5395 Amps for each solenoid. This value satisfies our benchmark measurement in the range of 0.5-0.6 Amps.

Other measurements showed that the magnetic field of the permanent toroidal magnet is constant and not time dependent. Using the Gauss meter, the field along the z-axis was found to be 2.8mT at the top center of the disk magnet, and 10mT around the edge of the disk.

Conclusions

The Fascination Levitron Revolution device levitates an object with magnetic fields from both permanent magnets and current induced solenoids. This method bypasses Earnshaw's theorem by using a feedback control system for the solenoids to equalize the magnetic forces and keep the disk magnet sustained in equilibrium. Through experimental procedure and analysis, the solenoids proved to change based upon the magnetic field values needed to keep the system in equilibrium.

This complex levitation system was analyzed and measured by amp-meter and Gauss meter for magnetic field measurements. Different experimental methods were used including measuring solenoid geometry, current, and magnetic fields. Measurements of the magnetic fields verified the theoretical analysis of the system. The methods applied in this paper can be applied to other magnetic levitation systems for analysis.

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