Levitation by Using Electromagnetic Force

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ABSTRACT: In the last decade, the field of electromagnetic suspension and levitation has become a topic of interest among researchers and industrial companies due to its possibilities of application, for example, in advanced ground transportation vehicles. This paper will focus on the controlled levitation of an object using the electromagnetic force. Each experiment was carried utilizing an electromagnet and a non-magnetic metal which were key elements in the determining of the variables on which the levitation depends. These factors will be examined and characterized in this paper.

Introduction – Aspects of Levitation

Levitation is the process by which an object is held above the ground in a stable position without using any support. One of the main points of this project was to achieve a controllable levitation. This means that it should be possible to maintain constant altitude of the levitating object. Also, it should be possible to change the levitating altitude by applying some external inputs.

To achieve levitation, methods like air pushing can be used (Figure 1). Nevertheless, electromagnetic force was chosen to be the best option for research carried in this paper, due to its benefits, which will be commented below.

Figure 1. Levitation by using air pushing.

As the first option, static magnets were seen as a possible solution because, depending on how their north and south poles are oriented, they can oppose the gravitational force. To achieve levitation, poles of the same type should face towards each other. This makes them repeal and, in turn, levitate (Figure 2). However, since they are static magnets, it is not possible to modify their magnetic fields. This causes incapability to control the altitude of the levitating object [1]. Moreover, static magnets are not stable when they repel each other (i.e. they tend to spin) and it is extremely difficult to keep them in a firm position. Another disadvantage of using static magnets was that they can only levitate other magnets, which was a restriction for our project.

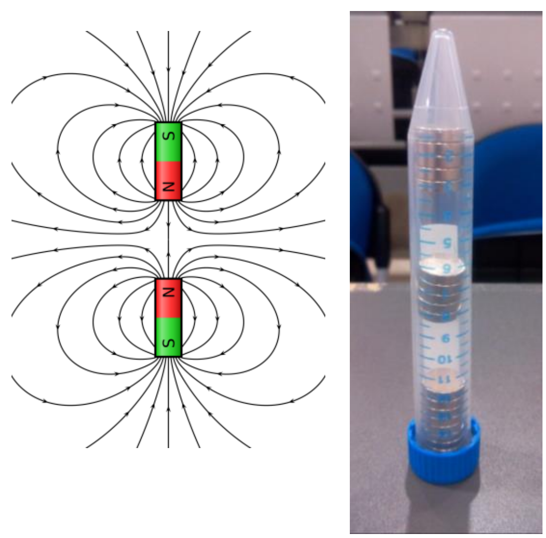

Figure 2. Magnetic field created by two static magnets that repel each other (left). Lab experiment done by applying the aforementioned principle. A container is needed to prevent magnets from spinning (right).

Incapability to change the strength of the magnetic field of static magnets was identified as a main drawback. To overcome this problem, it was decided to build an electromagnet. Briefly, electromagnet is a device composed of insulated copper wire, wound on a ferromagnetic core.

Current flowing through the wire causes the system to exhibit magnetic properties (Figure 3).

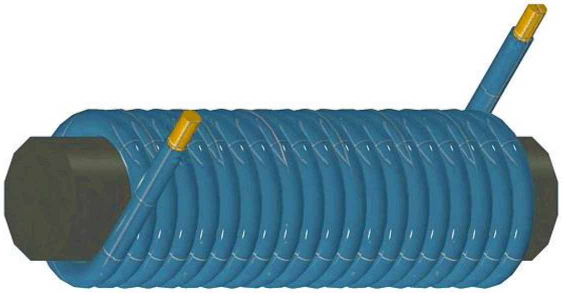

Figure 3. Electromagnet consisting of a coil of insulated wire wound on a ferromagnetic core. A core of ferromagnetic material like iron serves to increase the magnetic flux. The strength of magnetic field is proportional to the current through the winding.

The levitation by electromagnet can be controlled by modifying the intensity of current [2]. When varying the current, it was possible to increase or decrease the height of the lift, meaning that it is controllable. Moreover, electromagnets do not present a big restriction referring to the object they can levitate as they can lift any non-magnetic metals. Obviously, the levitating object should be made of conductive, non-magnetic material. Otherwise, the object would be attracted to the electromagnet.

Because of all the advantages, this study is going to focus on the levitation by using electromagnets.

Theoretical Background

Levitation of a non-magnetic metallic object is based on the induction phenomenon, which is based on current induced in the non-magnetic metal (I_{in}). The current can be induced in metallic object due to the variation of the flux in the electromagnet's magnetic field. The Lenz law postulates that the direction of the induced current is always such that it will oppose the change of magnetic field, produced by the original current. Consequently, the magnetic field created by the I_{in} is opposite to the electromagnet's original magnetic field, so they repel each other.

The magnetic flux can be considered as the number of magnetic lines that go through a surface. The variation of the flux of the electromagnet's magnetic field is related to the electromagnetic force by the Faraday's law of induction – in sense, larger the variation, higher the induced voltage. At the same time, the voltage is directly proportional to the I_{in} and the resistance of the wire through the Ohm's law. Finally, the magnetic field created by the induced current is dependent of the I_{in}. In conclusion, the magnetic field induced in the non-magnetic metal is directly proportional to the variation of the current intensity of the electromagnet, the surface and material of its core and the number of turns. For example, a significant increase on the current intensity of the electromagnet creates a stronger induced magnetic field that makes the non-magnet metal levitate in a higher altitude.

$$\Phi \propto ISN\mu_0\mu_r$$

$$\varepsilon = -\frac{\partial \Phi}{\partial t}$$

$$\varepsilon = I_{in}R$$

$$B = \frac{\mu_0\mu_r I_{in} N}{2r}$$

Here, Φ stands for magnetic flux, I is current intensity of the electromagnet, N is the number of turns in the electromagnet, μ_o is the free-space permeability, μ_r is the relative permeability of the metal core, t is the time, I_{in} is the induced current intensity, R is the resistance of the wire, B is the magnetic flux of a coil and r the radius of the coil.

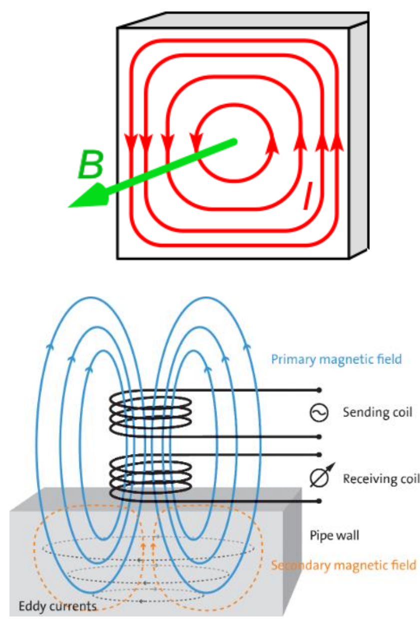

Figure 4. Eddy currents (top): red arrows represent the movement of the current, the green arrow is the magnetic field that creates the Eddy currents. Skin effect (bottom): blue lines, magnetic field; orange and grey lines, induced currents by skin effect.

The non-magnetic levitating object can be shaped in any geometrical figure. In the case it is a plate, Eddy currents and skin effect have to be taken into account (Figure 4). Eddy currents are loops of current induced in conductors by the variation of the magnetic field, due to the Faraday's law. The result of the sum of all this little loops of currents is a current that flows through the edge of the plate. Skin effect is a tendency of an alternating current to become distributed within a conductor mostly near its outer surface. The effect is more apparent as the frequency increases.

Experiments and Results

In this part, we will describe the measurements of the demonstrators that we build and present some results.

Let's Build an Electromagnet

In order to build a strong electromagnet, we need a core with high permeability. High permeability core channels the magnetic flux that would otherwise be scattered away from coil. From the supplies we had, we chose two ferromagnetic rods (both diameter of 28mm) with unknown permeability. Then we had to check which one has a higher permeability. We did this by measuring the attractive force between the rod and a static neodymium magnet (Figure 5). By measuring the attractive force, we observed that one rod had higher permeability than the other, so the rod with higher permeability was chosen as the core of the electromagnet [3].

Figure 5. Estimation of unknown permeability of two different ferromagnetic rods. The rod with higher permeability is attracted more by a static magnet and is, therefore, chosen as a core for electromagnet.

For wire that was wound around the rod, we had to choose wire parameters like material, diameter, and total length (i. e. number of turns). In Table 1 we present the resistivity and conductivity of different materials. It can be seen that copper is second only to silver in both parameters but has an added benefit of being cheaper and less soft than silver so copper was chosen as the material for the wire.

Table 1: Resistivity and conductivity of different materials at 20°C

Material	Resistivity [10^{-8} Ohm m]	Conductivity [10^{7} S/m]
Silver	1.59	6.3
Copper	1.68	5.96
Gold	2.44	4.1
Aluminium	2.82	3.5

Diameter of the wire is related to the resistance of the coil and the maximum current that the coil can sustain without overheating or melting. In Table 2 we show the maximum current trough the wire and resistivity with regards to the wire diameter.

Table 2: Wire diameter, resistivity and maximum current that it supports at 50°C

Diamer of wire [mm]	Resistivity [Ohm/m]	Maximum current [A]
0.3	0.273	1.49
0.5	0.098	3.08
1	0.025	8.28

The source we had (autotransformer) could yield maximal current of 6.6 A. From Table 2 it can be seen that wire diameter of 1 mm can sustain current of 8.28A and was, therefore, chosen for the electromagnet. A 1kg bundle of copper wire, diameter of 1 mm, was acquired and we calculated that the total length was 146m. With this length we calculated that we can wind 1400 loops around the core in 14 layers, with each having 100 individual loops. Assembled setup needed for first series of levitating experiments can be seen in Figure 6. It consists of electromagnet, autotransformer ($I_{\max}$ = 6.6 A), digital voltmeter, amp-meter, and connecting wires.

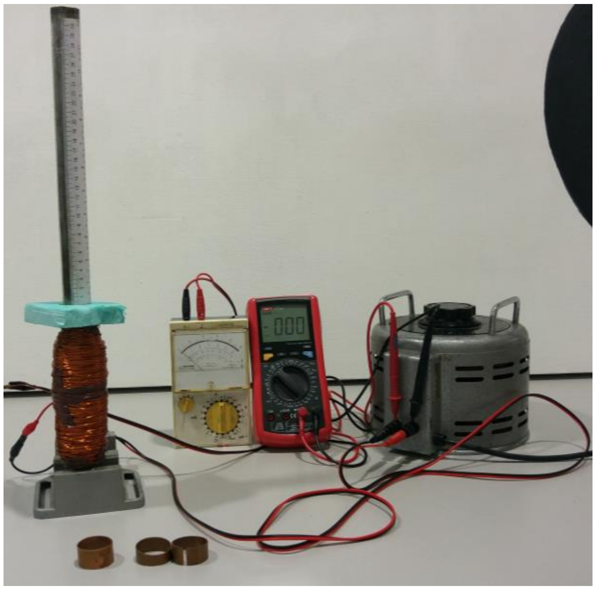

Figure 6. Setup for first series of levitation experiments.

Experiment 1: The Lift-off Current

For the first set of experiments, we chose three different copper rings as levitating objects. Each ring had diameter of 30 mm (to fit the iron core). Height of one ring was chosen to be 20 mm, whereas height of the other one was 10 mm. The third ring was cut along vertical axis (Figure 7).

Figure 7. Three rings as levitating objects for the first experiment.

The purpose of the ring with a slit was to demonstrate that levitation occurs due to currents induced inside the ring. If the ring is cut along the vertical axis, the current pathway is broken and conducting current inside the ring cannot be induced. It was observed that the slotted ring did not lift-off after it was mounted on the iron core of electromagnet, no matter of current intensity through the windings.

The fact that one uncut ring was higher than the other (with other dimensions being equal) implied that surface area where the induced current flows was larger. This, in turn, caused higher ring to be of lower resistance than the smaller one. Knowing this, we hypothesised that the bigger ring should have better levitation properties.

In the first experiment, we tried to relate number of turns of copper wire wound on the iron core to lift-off current. The lift-off current is intensity of current flowing through copper wire of electromagnet, needed to initiate levitation. Results are shown in Figure 8.

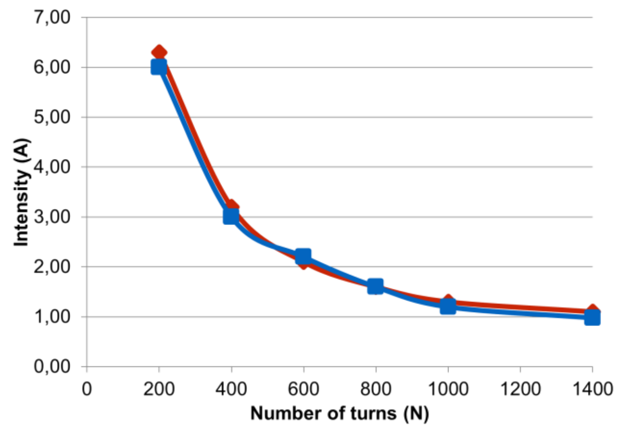

Figure 8. Lift-off current needed to levitate the ring with respect to the number of turns. Blue curve is for the higher ring while the red curve is for the smaller ring.

It can be seen that the lift-off current decreases while number of turns of copper wire increase. This result is expected because generated magnetic flux is directly related to number of turns (*N*).

Experiment 2: Levitating Altitude vs. N

For the second experiment, we kept intensity of current driving the electromagnet at constant value of 5 A. What we changed was number of turns of wire wound on electromagnet's core (*N*). For each step of 200, from 200 turns to 1400 turns, we measured altitude achieved by levitating rings. Results are shown in Figure 9. It can be seen that, as number of turns increased, both rings achieved higher altitude with same current. This results is, generally, expected. However, one should note that there was no significant difference in achieved altitude or in the lift-off current for higher and smaller ring. Although higher ring had larger surface area, making it able to accept larger current, its mass was also increased. The mass increase compensated benefits yielded from larger surface area. In this way, the larger ring was effectively equal levitating object as the smaller one.

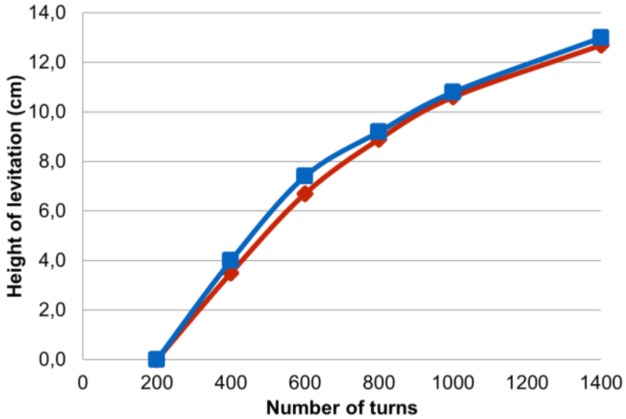

Figure 9. Achieved altitude of the rings with current set to 5A with respect to the number of turns. Blue=bigger ring, red = smaller ring.

The final experiment with electromagnet based on iron core, we measured the total mass able to levitate. We made a harness around the ring, in which we put weights in order to measure the maximum mass that the ring and this electromagnet were able to levitate. The total weight that we were able to levitate was 250 g.

Levitation of Electromagnet – the Hoverboard

For the second set of experiments, we decided to utilize induction of Eddy currents in a ground plane, when varying magnetic field was applied in perpendicular direction [4]. The ground plane was formed of four non-magnetic (aluminium) plates. In this case, the levitating object itself had to generate varying magnetic field. Therefore, it was chosen to make another electromagnet as the levitating object. This time, the electromagnet consisted only of a bundle of wire, with air core. Detailed information about the coil and the ground plane plates is given in Table 3.

The objective of the experiment was to hold the electromagnet in a static position without any mechanical support, only by using the magnetic field. In order to solve this problem, four aluminium plates were overlapped to create four separately induced magnetic fields that kept the electromagnet inside a magnetic barrier (principle shown in Figure 10). The characteristics of the electromagnet and the non-magnetic metal are discussed using the same arguments as in the first experiment. However, as we want to levitate a heavier object, the electromagnet, some changes are needed.

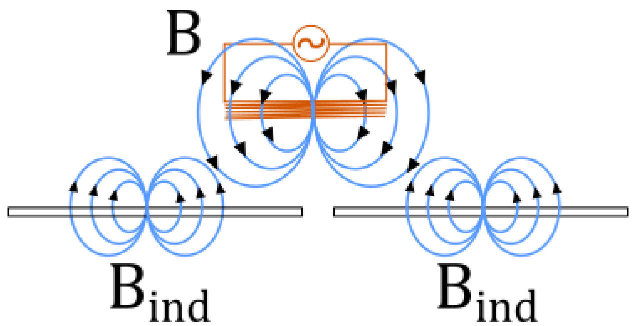

Figure 10. Scheme of the magnetic fields created in the second experiment. Magnetic field (B) created by the electromagnet. Induced magnetic field in the aluminium plates (B_{ind}).

As first, the diameter of the coil has been increased in order to have larger surface and, consequently, larger magnetic flux. After that, we reduced the height of the coil to have a more concentrated magnetic field as in this experiment there is no ferromagnetic core that would direct and concentrate the magnetic field lines. Finally, due to the increase of the surface of the electromagnet, a bigger surface of the non-magnetic metal was needed in order to have a stronger induced magnetic field. Final form of the experiment is shown in Figure 11.

Table 3. Characteristics of electromagnet and non-magnetic metal.

Electromagnet		**Ground plane**	
Material	Cu	Material	Al
Shape	Circular	Shape	Rectangle
Current intensity	5 A	Number of plates	4
Maximum current intensity	6,7 A	Dimensions	30 cm x 20 cm x 0,5 cm
Resistance	12,8 Ω	Resistance	0,5 Ω
Number of turns	363		
Length of the wire	194 m		
Diameter	17 cm		
Surface	227 cm2		
Thickness	2 cm		

Figure 11. Hoverboard formed of electromagnet as levitating object, above four symmetricaly placed aluminium plates. It is important to maintain a small gap between two adjacent plates in order to keep the levitating object firmly in place.

Several experiments were performed on this type of levitating assembly. As first, it was demonstrated that the coil placed above a single aluminium plate indeed levitates. However, the coil is highly unstable since it tends to flip over. Adding another aluminium plate, with a small gap between the two, stabilizes the coil along the border between the plates. That is, of course, if the coil was initially placed symmetrically, to cover both plates equally. However, the coil remains unstable in the other transversal direction. It is then demonstrated that adding two additional aluminium plates, placed transversally on top of previously fixed plates, entirely stabilizes the coil. Finally, we measured the total mass able to levitate, taking into account mass of the coil itself. We fixed current in the coil to 5 A and added weight carrying plate on the coil. Naturally, as we added more weight, the coil was losing its altitude. Finally, we measured that the total weight that we were able to levitate was 1003 g (coil + weights).

Conclusions

While doing all the experiments, it was proved that levitation is possible and it can be controlled. The results were achieved using an electromagnet. It is possible to regulate the altitude of levitating objects by changing current in the coil of electromagnet. In the first experiment, we used electromagnet formed of copper wire wound on iron core. The levitating object was a copper ring. In the second experiment, we levitated electromagnet with air core above four symmetrically placed aluminium plates. Obtained results are significant because in the last decades the field of electromagnetic suspension and levitation has become a topic of great interest, meaning that all this research could be part of a huge discovery.

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