TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

INTERNATIONAL BACCALAUREATE

PHYSICS EXTENDED ESSAY

Measuring Length of An Iron Rod With The Interaction Between Ferromagnetic Material and Inductance

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Word Count:

Abstract

This experimental study investigates the measuring length of an iron rod with the interaction between ferromagnetic material and inductance. Measuring such a small lengths by using a ruler is a major problem because of parallax etc. To prevent this, "How does the self inductance value change in inductance when the iron rod is imbedded in different lengths?" question was tested. Because the self inductance value (L) value will help us to calculate the length of the iron rod in the solenoid. The experiment was made in 3 parts. First, when the inductance was empty, self-inductance value was found. After this, to find the permeability of iron rod that was used in the investigation, iron rod was fully imbedded into the solenoid, resonant frequency was read and permeability was calculated. Thirdly, 11 different lengths of iron rod was imbedded into the solenoid and by using their resonant frequencies, L values were calculated and by using another equation, how much length of the iron that was imbedded into the inductance was found. At the beginning of the experiment, how much length that will be imbedded was measured by caliper. These values were accepted as theoretical values, lengths. So, the percentage errors were calculated using the data gathered. Errors are varied from %1.37 to %4.92. The results were plotted on a graph and this graph showed the relation between how much length is imbedded vs. L values. Those results showed that as the imbedded lengths decrease, self-inductance values decrease directly proportional.

Word Count: 244

Contents

1. Introduction and Presentation

Scope of Work:

Measuring the length of a material seems relatively simple however it becomes complex when RLC circuit is used. In a physics textbook, I saw the working principle of a profilometer which is used for measuring a surface's profile to quantify its roughness. Measuring a certain length by a ruler is generally inaccurate when it is compared to electronic devices as shown below. That is why, by using a electronic system or computer controlled measurements which decreases the errors are the starting point of this investigation. Therefore, measuring the length of a material by using ferromagnetic material(iron) came to my mind. Investigating such a thing might be interesting.

This essay is an attempt to study the phenomenon of measuring length of a material by the help of a ferromagnetic material and to investigate its consequences. Throughout the experiment, iron rod was used as a ferromagnetic material when RLC circuit is runned. During the investigation different lengths of an iron rod was imbedded into the solenoid, and value of resonant frequency is measured. By doing several calculations, length of the iron rod that was imbedded in the solenoid was calculated. Before each trial, inserted lengths of the iron rod was measured by using caliper to verify the obtained results. However, uncertainties of the caliper should be considered. An evaluation of the reliability of the measurements and claims assesses the validity of the conclusions made on this subject.

[1]

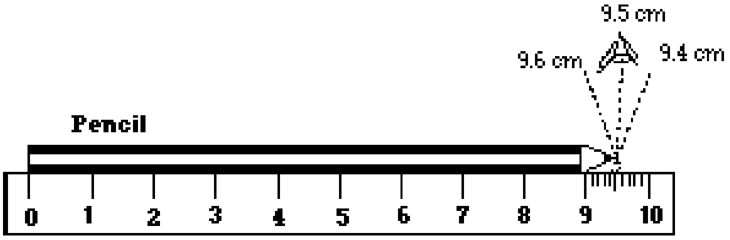


Fig 1. Example of parallax in reading the position of a point from a ruler.

2. Background Information and Literature:

Ferromagnetisim

First of all, ferromagnetism is the basic mechanism by which certain materials (such as iron) form permanent magnets, or are attracted to magnets. Ferromagnetism is the only type that creates strong forces enough to be felt. Other types of magnetism such as paramagnetism and diamagnetism respond very weakly to magnetic fields.[2]

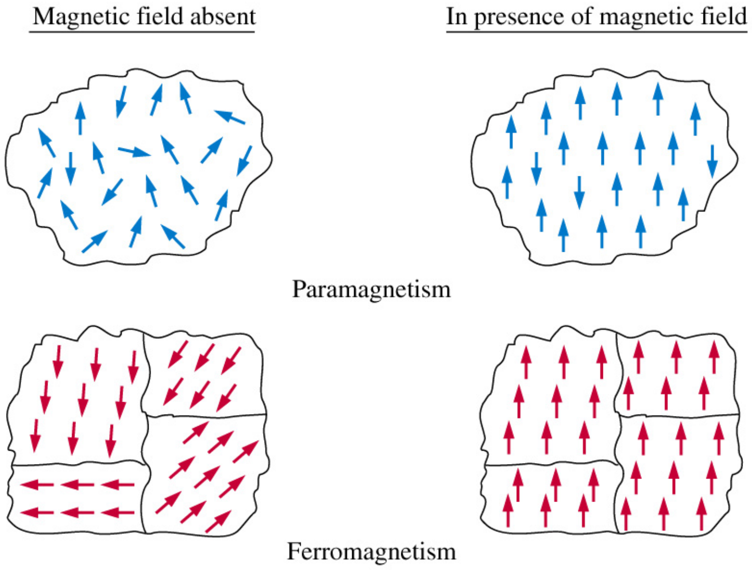


Fig 2: Figure shows the difference between paramagnetism and ferromagnetism in the presence of a magnetic field.

Permanent magnets are either ferromagnetic or ferrimagnetic, as are other materials that are noticeably attracted to them. Common ferromagnetic substances that create strong forces are iron (Fe), nickel (Ni) and cobalt (Co).

Vacuum Permeability

Permeability is very important for this essay because magnetic field changes when the iron rod is imbedded into the solenoid. Therefore I have to explain the vacuum permeability. The physical constant, μ_0, commonly called the vacuum permeability, is an ideal, physical constant, which is the value of magnetic permeability in a classical vacuum. Vacuum permeability can be derived when a magnetic field is produced by an electric current. In the reference medium of classical vacuum, μ_0 has an certain defined value:

$$\mu_0 = 4\pi\times10^{-7}\ \text{H/m}$$ [3]

What is a RLC circuit?

A circuit which is consisting of a resistor, an inductance and a capacitor connected in series or in a paralle is called as RLC circuit but in this investigation series RLC circuit was used. In addition to that, three of these elements give their first letters to the name of the circuit. ‘R’ for resistor, ‘L’ for inductance and ‘C’ for capacitor.

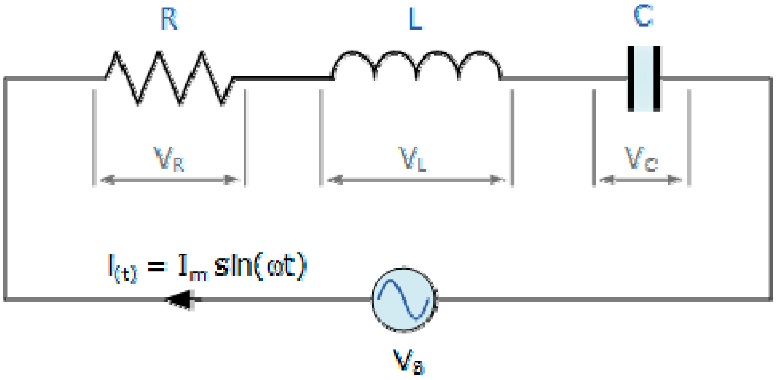


Fig 3: The series RLC circuit above has a single loop with the current flowing through the loop being the same for each circuit element. Therefore the individual voltage drops over each element (R,L,C) in the circuit; and these elements will be out of phase with each other as it is shown below:

$$i_{(t)} = I_{max} \sin(\omega t)$$ [4]

The current is in phase with the voltage across a resistor, V_R.

Therefore, V_L and V_C are in opposite direction to each other.

Here is the elements of the RLC circuit;

Electrical Resistance

The electric resistance of a conductor is defined as the potential difference across its ends divided by the current flowing through it. The SI unit of electrical resistance is the ohm (Ω). All materials except superconductors which have zero resistance, show some resistance.

Fig 4: This figure shows an example of a electrical resistor. [5]

The ratio of voltage across resistance to current through it is defined as the resistance, while the Conductance (G) is the inverse:

$$R = \frac{V}{I}, \qquad G = \frac{I}{V}, \qquad G = \frac{1}{R}$$

During the experiment, resistance was determined by looking the colour on it and by using the electronic colour code. Colourbands are widely used principally in resistors because they are printed easily on very small components and decreasing construction costs.

Capacitance

A capacitor is a passive two-terminal electrical component used to store energy electrostatically in an electric field. All capacitors which are seperated by a dielectric contain at least 2 electrical conductors. For example, one common construction comes out of metal foils seperated by a thin layer of insulating film.

Fig 5: Figure shows the capacitor with 100 μF. This is the same capacitor that I used in the investigation. [6]

An electric field develops across the dielectric, causing –ve charges on one plate and +ve charges on the other plate when there is a potential difference across the conductors. Therefore, energy is stored in the electrostatic field. In addition to that, the SI unit of capacitance is farad, which is equal to one C/V.

Inductance

In electromagnetism and electronics, inductance is the property of a conductor by which a change in current in the conductor creates a voltage in both the conductor itself (self-inductance) and in any nearby conductors (mutual inductance). These effects are derived from two fundamental observations of physics: First, that a steady current creates a steady magnetic field and second, that a time-varying magnetic field induces voltage in nearby conductors. According to Lenz's law, a changing electric current through a circuit that contains inductance, induces a proportional voltage, which opposes the change in current (self-inductance). The varying field in this circuit may also induce an e.m.f. in neighbouring circuits (mutual inductance). [7]

Fig 6. This is one of the inductors that is used in the experiment. [8]

Resonance

An important property of this RLC circuit is its ability to resonate at a specific frequency, the resonance frequency, f_0. In this essay, however, angular frequency, w_o, is used which is more mathematically convenient. They are related to each other by a simple proportion,

$$w_o = 2\prod f_0$$ [9]

Resonance in AC circuits implies a special frequency determined by the values of the resistance, capacitance, and an inductance. When the RLC circuit is in series, the case of resonance is generally straightforward and it is described by zero phase and minimum impedance.

When the impedance of the circuit is at minumum, resonance frequency occurs. This occurs because the inductor's and the capacitor's impedances are eqaual each other but in opposite direction at resonance. Therefore they cancel out. If the inductor and capacitor are in parallel, they have a maximum impedance rather than a minimum. Because of this they are generally characterized as "antiresonators".

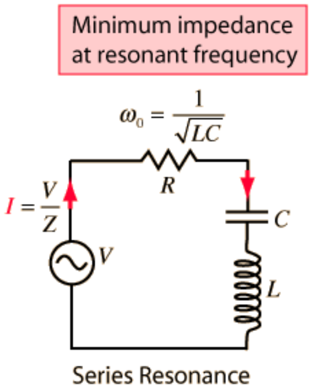


Fig 7: This figure shows the RLC circuit in series at resonant. It also can be seen that there is a minimum impedance at resonant frequency. [10]

In a series RLC circuit, for the known value of R and C; L value can be found in resonant case by using the equality below:

$$L = 1/ [(2\prod f)^2 \times C]$$ [11]

If the Inductor is in the air medium, with respect to the properties of inductance, inductance value can be found as shown below;

$$L = \mu_0 \times N^2 \times A / l$$ [12]

N is the number of turns of solenoid, A is the cross section area of the solenoid and l is the length of it. Where μ_0 is the vacuum permeablity.

If a ferromagnetic material like iron rod is placed into a inductance, medium will be changed, therefore below formula can be used to measure the L value and permeability of iron rod that was used throughout the investigation;

$$L = \mu_{iron} \times N^2 \times A / l$$ [13]

Above formula explains the situation where all the iron rod is imbedded into the solenoid.

When an iron rod is imbedded into a solenoid partially, sum of the length of an iron rod that is in the solenoid and the empty part that is remained in the solenoid will give the whole length of the solenoid which is equal to 2.7 cm.

$$L = L_1 + L_2$$ [14]

Where; L is equal to self inductance value when the iron rod is imbedded and resonant frequency is determined, L_1 is the empty part of the solenoid and L_2 is the part of the solenoid with the iron rod.

Therefore, by using the formula below l_1, imbedded iron rod, will be found:

$$L = N^2 \times A [(\mu_0 l_1 + \mu_{iron} (l- l_1))] / l_2$$ [15]

3. Experimental Setup and Description

Research Question:

How does the self-inductance's (L) value change in inductance when the iron rod is imbedded in different lengths?

Variables

Independent Variable:

Imbedded length of the iron rod in the solenoid

Dependent Variable:

Self-inductance (L) value in the RLC circuit

Controlled Variables:

- Resistor (100 Ω - in each trial, same resistor was used; last colour of it was silver)
- Capacitance (100 µF – in each trial, same capacitance was used)
- Iron Rod (1.6 cm of radii, length of 5.0cm – same rod was used in each trial)
- PASCO Science Workshops 750 Interface
- Input voltage (amplitude with 3A – same amplitude was arranged as 3A in each trial)
- Cross sectional area of the solenoid (3.88 ± 0.39 cm^2 – same solenoid was used in every trial)

Materials:

- PASCO Scientific EM-8656 AC/DC Electronics Labaratory
- PASCO Voltage Sensor (±10 V)
- PASCO Science Workshops 750 Interface (±35 V)
- Data Studio
- 2 Wires (one of them input, 30 cm of crocodile wire)
- Capacitance (100 µF)
- Resistor (100 Ω ± 10% - we used colour code to determine the resistor and the last colour of it was silver therefore it has a tolerance of 10%)
- Inductance (L= 8.2 mH)

- Iron Rod (1.6 cm of radii, length of 5.0 cm)
- Caliper (± 0.1 mm)

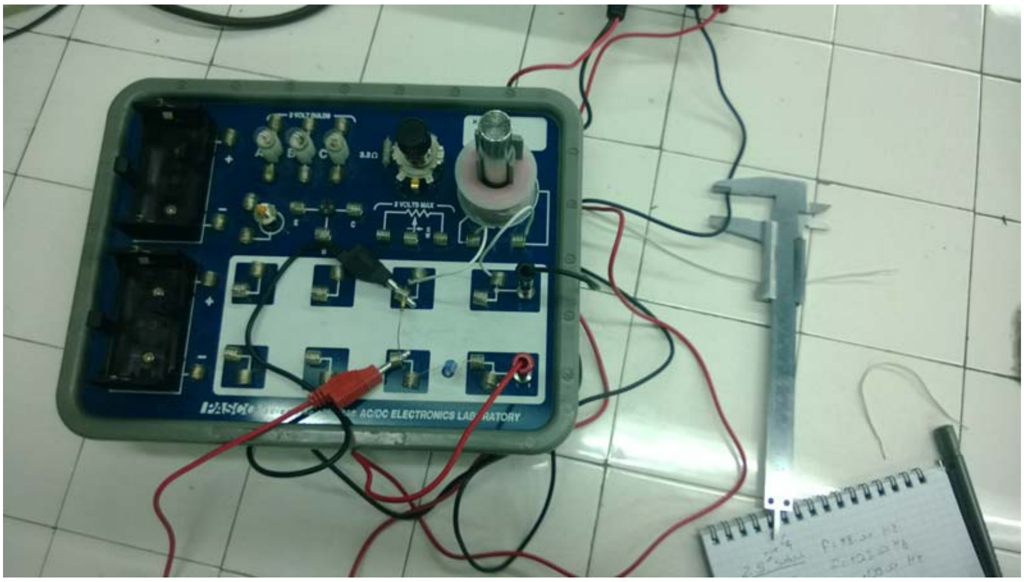


Fig 8: This figure represents the experiment apparatus. There are 2 crocodile wires (red and black), a caliper, resistor with 100 Ω, capacitor with 100 μF, inductor with 8.2 mH, iron rod (1.6 cm of radii, length of 5.0 cm), PASCO Scientific EM-8656 AC/DC Electronics Labaratory, voltage sensor and an interface.

Measuring Instrument Description [16]

The instruments used to collect data include: PASCO Scientific EM-8656 AC/DC Electronics Labaratory, PASCO Voltage Sensor, PASCO Science Workshops 750 Interface.

1. Science Workshop 750 Interface

In this investigation I will use the 750 interface to create a "variable battery" whose voltage can be changed.

2. AC/DC Electronics Lab Circuit Board

I will also use the circuit board. This time I will use the inductor as a connector pads for resistors and capacitors.

3. Current & Voltage Sensors

Both current and voltage sensors follow the convention that red is +ve and black as –ve. That is, the current sensor records currents flowing in the red lead and out the black as positive. The voltage sensor measures the potential at the red lead minus that at the black lead.

EM-8656 was required to set the RLC circuit.

Method:

1. RLC circuit is constituted in series with resistor (R), capacitor (C) and an inductance (L).
2. Input voltage is constituted with an amplitude of 3A.
3. Then Input voltage is chosen as sine wave.
4. After this arrangement, the resonant frequency value of RLC circuit is found.
5. To find L (inductance), cross sectional area (A), length and number of turns (N) of solenoid is measured.
6. By using these, when solenoid is empty L value is found.
7. Accuracy of the values are verified by using the L value in manual.
8. Iron rod is inserted into the L, then resonant frequency is found. Iron rod is taller than the solenoid therefore rod taşmak from the solenoid. To prevent this, I used a support system which held the rod 1.15 cm above the solenoid and 1.15 cm below the solenoid.
9. By using this resonant frequency, L (with an iron rod) is calculated.
10. Iron rod that was used along the experiment may not be pure. Therefore, a formula is used to calculate the permeability of iron rod.
11. Iron rod is imbedded into a solenoid in different lengths.
12. Lenghts of the iron rod are measured by caliper to verify the results at the end of the investigation.
13. Resonant frequency is calculated for each of lengths respectively.
14. From the formula: $L = L_1$ (empty part) + L_2 (part of the solenoid with an iron rod) is equalised with the L which is found by a resonant frequency with the mathematical formula.
15. By this equalisation, length of an iron rod in solenoid is found.

4. Experimental Procedures and Recorded Results

Part A:

When the inductance is empty resonant frequency value was read. According to the programme, data studio, $f = 175.75$ Hz

by using the formula;

$$f = 1 / (2\prod\sqrt{LC})$$

where;

f = frequency (Hertz)

L = self-inductance (Henry)

C = capacitance (Farad)

L (self-inducatance) value was found as 0.0082 Henry as shown below;

$$L = 1/ [(2\prod f)^2 \text{ x } C]$$

$$L= 1/ [\ 2\prod 175.75)^2 \text{ x } 0.0001]$$

$$L = 0.0082 \text{ H}$$

To verify the L (self-inductance) value, another equation was used:

$$L = \mu_0 \text{ x } N^2 \text{ x } A / l$$

where;

L = self-inductance (Henry)

N = number of turns of solenoid = 674

A = cross section of solenoid (cm2) = 3.88 cm^2

l = length of solenoid (cm) = 2.70 cm

μ_0 = vacuum permability [V·s/(A·m)] = $4\pi \times 10^{-7}$ V·s/(A·m)

$$L = 4\pi \times 10^{-7} \text{ x } 6742 \text{ x } 3.88 \text{ x } 10^{-4} / (2.7 \text{ x } 10^{-2})$$

$$L = 0.0082 \text{ Henry}$$

Part B:

Throughout the experiment, length of 5.0 cm and radii of 1.6 cm of iron rod was used. However, iron rod that was used may not be perfectly pure. That's why permeability of iron will be calculated in this section.

When the inductance is full with iron rod, value of resonant frequency was read and to find the permeability an equation was used below:

Resonant frequency when iron rod was inserted fully into the solenoid is 89.6 Hertz

$$L = 1/ [(2\prod f)^2 \times C]$$

$$L = 0.032 \text{ Henry}$$

$$L = \mu_{iron} \times N^2 \times A / l$$

$$(L \times l) / (N^2 \times A) = \mu_{iron}$$

where;

L = self-inductance, 0.0082 H

l = length of iron rod that is in the solenoid, 2.70 cm

N = number of turns of solenoid = 674

A = cross section of solenoid (cm^2) = 3.88 cm^2

$$\mu_{iron} = (0.032 \times 2.7 \times 10^{-2}) / (674^2 \times 3.88 \times 10^{-4})$$

$$\mu_{iron} = 4.83 \times 10^{-6} \pm 5.00 \times 10^{-8} \text{ H/m}$$

Part C:

In this part different lengths of iron rods were imbedded. For each of them resonant frequencies were read. By using the resonant frequency, L (self-inductance) values were calculated and by using another equation, how much length that was imbedded into the inductance was found.

Along the experiment 11 different lengths were imbedded into the solenoid and for each of them value of resonant frequencies were read and L (self-inductance) values were calculated. After these calculations, l_l (calculated imbedded length) was found.

Imbedded Lengths of Iron Rod (± 0.1 cm)	Resonant Frequencies (± 0.1 Hz)
2.4	94.2
2.2	97.30
2.0	100.4
1.8	104.3
1.6	108.7
1.4	112.2
1.2	118.7
1.0	123.5
0.8	130.1
0.6	137.9
0.4	147.8

Table 1: This table shows the variations of resonant frequencies when imbedded lengths of iron rod was changed.

For the imbedded length of 2.4 cm, L (self-inductance) value was found:

$$L = 1/ [(2\prod f)^{2}\ x\ C]$$

$$L = 1 / [(2x\prod x94.2x0.0001)]$$

$$L = 0.029\ H$$

Imbedded Lengths of Iron Rod (±0.1 cm)	Resonant Frequencies (±0.1 Hz)	Self-inductance values (± 0.001 H)
2.4	94.2	0.029
2.2	97.3	0.027
2.0	100.4	0.025
1.8	104.3	0.023
1.6	108.7	0.021
1.4	112.2	0.020
1.2	118.7	0.018
1.0	123.5	0.017
0.8	130.1	0.015
0.6	137.9	0.013
0.4	147.8	0.012

Table 2: This table shows the calculated self-inductance values for each of the imbedded lengths.

$$L = L_1 + L_2$$

where;

L = self-inductance (Henry)

L_1 = empty part of the solenoid (cm)

L_2 = part with an iron rod (cm)

$$L = N^2 \text{ x } A \, [(\mu_0 \, l_1 + \mu_{iron} \, (l - l_1))] \, / \, l_2$$

By using the equation above, l_1 -imbedded length of an iron rod- will be found. Here is one of the calculation to find l_1 for the imbedded length, l = 2.4 cm;

$$L = 674^2 \text{ x } 3.88 \text{ x } 10^{-4} \left[(4\pi \times 10^{-7} \text{ x } l_1 + 4.83 \text{ x } 10^{-6} (2.7 \text{ x } 10^{-2} - l_1))\right] / (2.7 \text{ x } 10^{-2})^2$$

$$0.029 = 674^2 \text{ x } 3.88 \text{ x } 10^{-4} \left[(4\pi \times 10^{-7} \text{ x } l_1 + 4.83 \text{ x } 10^{-6} (2.7 \text{ x } 10^{-2} - l_1))\right] / (2.7\text{x}10^{-2})^2$$

$$l_1 = 2.35 \text{ cm}$$

Imbedded Lengths of Iron Rod (±0.1 cm)	Calculated Lengths-l_1- (cm)
2.4	2.35
2.2	2.15
2.0	1.96
1.8	1.74
1.6	1.53
1.4	1.38
1.2	1.14
1.0	0.97
0.8	0.78
0.6	0.59
0.4	0.39

Table 3: This table shows the comparison of calculated l_1 values and actual imbedded lengths.

Error Calculation:

$$\% \, error = \frac{|experimantal\ value - literature\ value|}{literature\ value} * 100$$

For the imbedded length of 2.40 cm, percentage error is shown as below:

$$\% \, error = \frac{|2.40 - 2.35|}{2.40} * 100$$

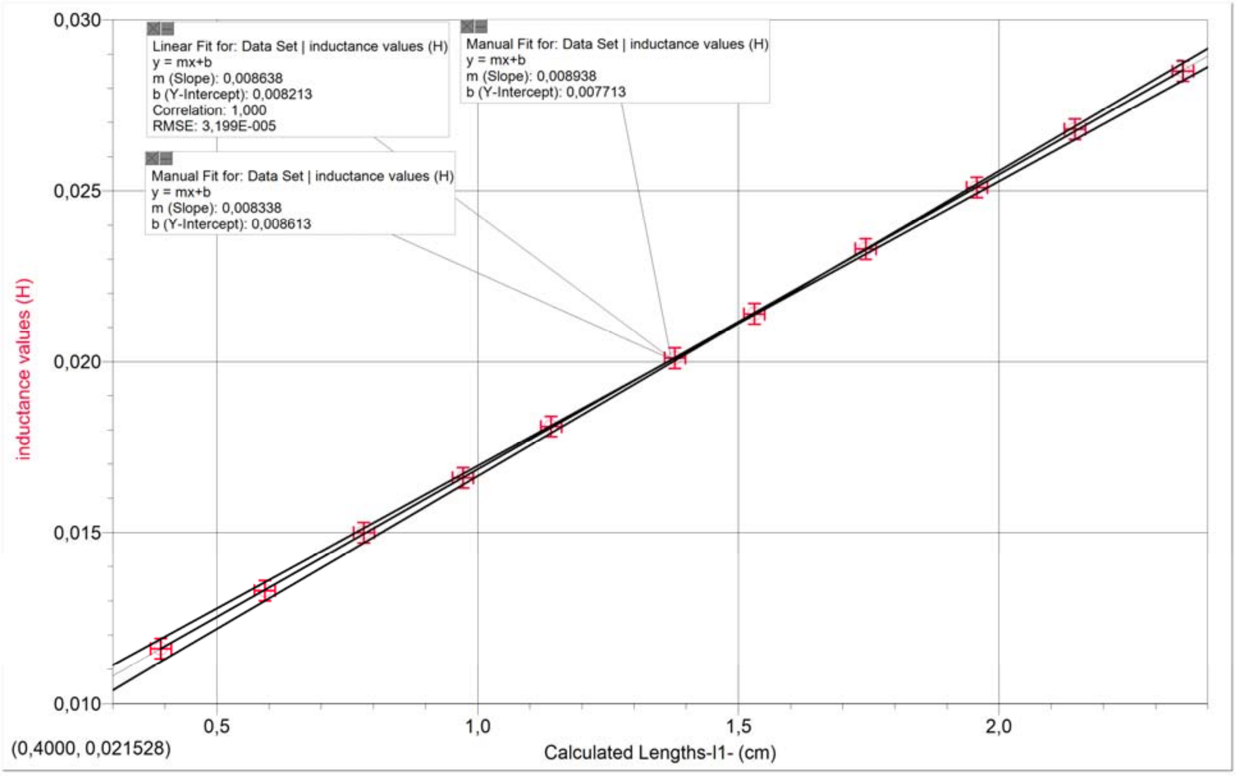
$$\% \, error = 1.98\%$$

Imbedded Lengths of Iron Rod (±0.1 cm)	Calculated Lengths-l_1- (cm)	% Error
2.4	2.35	1.98
2.2	2.15	2.48
2.0	1.96	2.14
1.8	1.74	3.11
1.6	1.53	4.35
1.4	1.38	1.55
1.2	1.14	4.92
1.0	0.97	2.81
0.8	0.78	2.25
0.6	0.59	1.37
0.4	0.39	1.91

Table 4: This table shows the percentage error of calculations.

Calculated Lengths-l_1- (cm)	L (self-inductance) values (± 0.001 H)
2.35	0.029
2.15	0.027
1.96	0.025
1.74	0.023
1.53	0.021
1.38	0.020
1.14	0.018
0.97	0.017
0.78	0.015
0.59	0.013
0.39	0.012

Table 5: This table shows the self-inductance values when the different lengths of iron is imbedded into the inductance when resonant frequency is determined.



Graph 1. This graph shows the correlation between calculated lengths (l_1) and self inductance (L) values. It can be seen that l_1 and inductance are in a correlation to each other. Also, there are two worst lines, and 1 best fit line in the graph.

$$\text{Graph Slope} = m_{best} \pm \Delta m$$

Where slope uncertainty is;

$$\Delta m = (m_{high} - m_{low}) / 2$$

$$\Delta m = (0.0089 - 0.0083) / 2$$

$$\Delta m = 0.0003$$

Therefore slope is equal to 0.0086 ± 0.0003

5. Discussion and Evaluation

This investigation has lead several interesting observations and results. First of all, I noticed that as imbedded length of an iron rod in the inductance increases, self-inductance value increases. It also can be seen in the Graph 1.

The results that are obtained from several calculations are accurate. All of the 11 different lengths that were imbedded into a inductance are very close to the actual value. Also, range of the errors is between %1.37 and %4.92. This is originated from the limitations that we encountered during the investigation. Firstly, before inserting the iron rod into the solenoid, length that will be imbedded, was measured by using the caliper. Verification process was also done with respect to it. However, uncertainty of the caliper is 0.1 mm but throughout the experiment this was neglected. That may have caused results to be inaccurate. When we think about the circuit that was set with PASCO Scientific EM-8656 AC/DC Electronics Labaratory, we can assume that the resistor and capacitor as a solenoid. If it is assumed like this, another calculation for L (self-inductance) value is necessary. This will change the results. Another limitation that we encountered during the whole process is, I could not find a iron rod with the same length of the inductance: Our iron rod was 5.0 cm however length of the solenoid is 2.7 cm. While I was calculating the permeability of iron, rod was **taşmak** from the solenoid. To prevent this, I used a support system which held the rod 1.15 cm above the solenoid and 1.15 cm below the solenoid. By this way, we neglected these parts and permeability of iron rod was calculated. A rod with the same length of solenoid should be used in order to calculate the permeability of iron rod exactly.

At the beginning, when the inductance is empty resonant frequency value was read and by using the formula $f = 1 / (2\prod\sqrt{LC})$, self inductance (L) value was found as 0.0082 Henry, to verify this when the solenoid is empty, a formula $L = \mu_0 \times N^2 \times A / l$ was used. According to these calculations self-inductance value was found as 0.0082 Henry too. This shows the calculations that we made are reliable. Also according to the Graph 1, it can be seen that the best fit line passes through the all data points and the slope of the best fit line is positive and the data points are very close to the best fit line so imbedded lenght and self-inductance are said to be positively correlated. In addition to that a straight line which passes through the origin represents direct proportionality between the two variables plotted, $y = mx$. However in Graph 1, best fit line does not pass through the origin, so in that case it can be said that there is a simple linear relationship, $y = mx + c$. In the graph best fit line has a slope of 0.0086 and “c” value is 0.0082. Also correlation is 1.000. Moreover, according to the error propagation, uncertainty of the slope is found as 0.0003 which means datas are in the range of 0.0086 ± 0.0003.

This investigation was originated from the dektak profilometer and I think it is necessary to compare our system with the profilometer’s system. To start with the measuring limit;

Our measurements were mainly focused on the iron rod and solenoid. If the solenoid is not tall enough, we can not do specific measurements. We can only do measurements depend on the length of the solenoid. This is also similar with the profilometer. A profilometer can only measure up to 20 mm of sample thickness. In addition to that, our mechanism can work as a profilometer. If we fixate our solenoid at a constant height and then, when we imbed iron rod in it, rod will not cling anything in the solenoid. Therefore it will prolapse a little a bit. By this way it will be in contacted with the surface (surface that the thickness will be measured). In this case, some part of the iron rod will be in the solenoid, and the other part will be under the solenoid as shown in the figure 9. By using the equations, length of the iron rod in the solenoid can be found. And then, we have to take measures for the other surface which is above the previous surface. When we imbed the iron rod like the previous one, iron rod will be in contact with this surface too. However, part of the iron rod in the soleniod will increase. We can find the length of the iron rod in the solenoid by using several formulas. And the difference between these two measures will give the surfaces thickness. Beside, it can work as a profilometer, in our system, we use a radii of 1.6 cm of cyclindrical iron rod which may not detect any milimetric changes. A tiny stylus should be used in order to solve this problem because profilometer uses stylus, radius of 12.5 um.

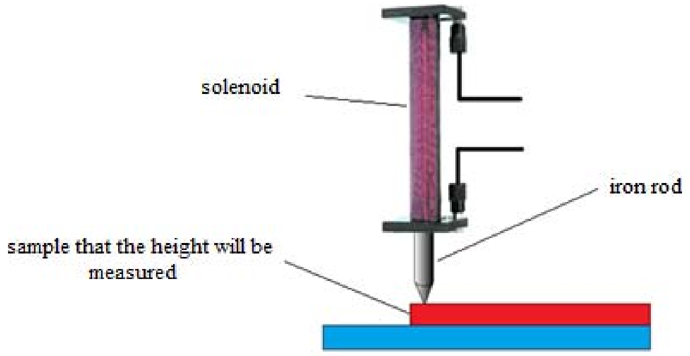


Fig 9: Figure shows how our system can work as a profilometer

6. Appendix

Graphs below show the resonant frequencies when different lengths of iron rod is imbedded into a inductace.

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