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Analysis and Determination of Self-Inductance through Direct and Indirect Measurements Methods

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ABSTRACT
Practicum is an activity that helps students to understand an abstract concept. One of the concepts in physics that requires practicum is the concept of electricity. Inductance is an electrical quantity studied in high and vocational high schools. This study aims to determine the inductor's inductance value using several methods and analyze the most suitable method for determining the inductor inductance value. The inductor used is a commercial inductor with a color band code with an inductance value of 2.7 mH and a tolerance of 10%. Inductor inductance measurements were carried out using a benchtop LCR meter, handheld LCR meter, series RLC method, and LC resonance method. Each measuring instrument requires a frequency setting: refer to the manual for benchtop and handheld LCR meters, the resonant frequency for the serial RLC method, and adjusting the AFG (arbitrary function generator) frequency. Hence, a clear oscillation pattern is visible on the oscilloscope. The results of this study indicate that measurements using benchtop LCR meters, handheld LCR meters, and LC resonance methods produce inductance values within the inductance tolerance limits.

INTRODUCTION

Practicum is an activity that can support the understanding of physics concepts. By doing practicum, students can practice basic experimental skills such as using measuring instruments, choosing data collection methods, and processing measurement data [1]. Practicum can also improve cognitive, affective, and psychomotor abilities [2]. The essential aspect needed in carrying out practicum activities is measurement, which is the determination of a quantity against a standard or unit of measure.

One of the topics that require practical activities is electricity. Electrical topics studied in high school (SMA) include direct current electricity, which studies Ohm's law, Kirchhoff's law, series, and parallel circuits, and alternating current electricity, which studies RLC circuits and their circuit characteristics. In comparison, the electricity topics studied in vocational high schools (SMK) include electrical measuring instruments and measuring electrical components. On this topic, students are expected to be able to explain the use of electrical measuring instruments, understand RLC passive components, use electrical measuring instruments, and measure passive components.

An inductor is an example of a passive component that can store energy in the form of a magnetic field [3] which consists of several windings of air-core wire or a ferromagnetic material such as iron or ferrite. The inductance value of the inductor depends on the shape, size, and the core's material. In contrast to the resistance values of resistors and capacitor capacitance, which can be measured using a multimeter, inductor inductance values cannot be measured using a multimeter. However, they can be measured directly with an LCR meter and indirectly using the series RLC and LC resonance methods. LCR meters can measure resistance, capacitance, and inductance. LCR meter can be directly used to measure inductance by connecting the LCR meter probe to the legs of the inductor. By setting the correct measuring frequency, the inductance value will be obtained.

The series RLC circuit is a circuit consisting of a resistor (R), inductor (L), and capacitor (C) connected to an alternating voltage source with frequency (f). In this circuit, the value of the inductor voltage (V_{Lrms}) and the current flowing in the circuit (I_{rms}) can be determined so that the value of inductive reactance (X_L) can be calculated using the equation:

$$X_L = \frac{V_{Lrms}}{I_{rms}} \tag{1}$$

Furthermore, the inductance value of the inductor (L) can be calculated using the following equation:

$$L = \frac{X_L}{2\pi f} \tag{2}$$

The LC circuit consists of a capacitor (C) and an inductor (L) arranged in series connected to a signal generator with a square wave. In a pure LC circuit, the capacitor charge and current in the circuit change sinusoidally with time [4]. This sinusoidal pattern experiences attenuation at the amplitude seen on the oscilloscope, which is known as a damped oscillation due to the resistance of the component or signal generator.

Determining the inductance of the inductor with the LC resonance method can be done by looking for the resonant frequency (f_0) shown on the oscilloscope. The resonant frequency occurs when the current in an alternating electric circuit is maximum when the inductive reactance value equals the capacitive reactance $X_L = X_C$. If the resonant frequency and capacitance values are known, then the inductance value can be calculated using the following equation:

$$L = \frac{1}{4\pi^2 f_0^2 C} \tag{3}$$

In previous studies, inductance measurements using the RLC and LC methods have been carried out with different circuits and several additional components, such as diodes and ICs [5] [6] [7]. In this study, the circuit used is more straightforward, and the components are easy to obtain. The teacher can use the inductance measurement method described previously to carry out practical activities on electricity.

METHOD

The inductor used in this study is an inductor with color bands with an inductance of 2.7 mH with a tolerance of 10%. The inductor will be measured directly using an LCR meter and indirectly using a series RLC circuit and LC resonance.

Inductance measurement with LCR meter

This study uses two types of LCR meters, namely the Benchtop LCR meter GWinstek LCR-819 series with frequency specifications covering 12Hz – 100kHz and basic accuracy of 0.05% and the LCR meter Handheld Lutron LCR-9184 with specifications for five different test frequencies, namely 100 Hz, 120 Hz, 1 kHz, 10 kHz, 100 kHz, and basic accuracy of 0.8%.

***Fig 1**. Benchtop LCR meter*

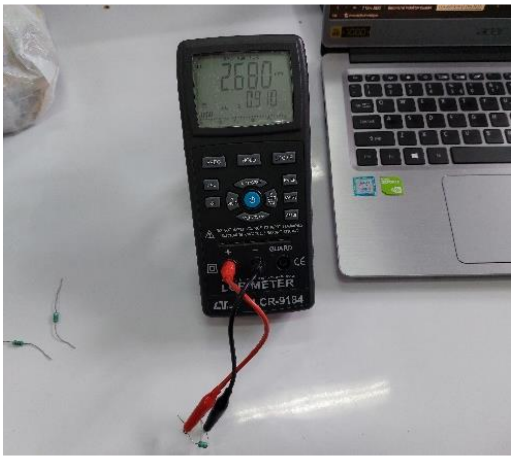

***Fig 2**. Handheld LCR meter*

Inductance measurement steps using a benchtop LCR meter:
1. Select the L/Q mode on the LCR meter
2. Set the frequency to 1 kHz
3. Connect the LCR meter probe with the inductor legs
4. The symbol L indicates the inductance value on the display

Inductance measurement steps using a handheld LCR meter:
1. Select L mode by pressing the L/C/R button
2. Set the frequency to 1 kHz
3. Connect the LCR meter probe with the inductor legs
4. The inductance value will be directly read on the screen.

Inductance measurement with the series RLC method

The tools and materials needed to measure inductance with this method are a signal generator, oscilloscope, multimeter, 11 resistors with different resistances, capacitors, and inductors.

Determining the inductance value using the series RLC circuit method needs to fulfill certain conditions, i.e., the circuit must be inductive so that the voltage across the inductor is large enough. Fulfilling these conditions can be done by using a large capacitance or changing the source frequency's value so that the results are close to the actual value. In this study, variations in the frequency value were carried out by changing the frequency value in the generator signal to obtain an inductance value close to the actual value. The series RLC circuit arrangement can be seen in Figure 3.

***Fig 3**. Series RLC circuit arrangement*

The steps for determining the frequency of the signal generator and the inductance of the inductor are as follows:

1. The serial RLC circuit scheme used in this study is shown in Figure 4.

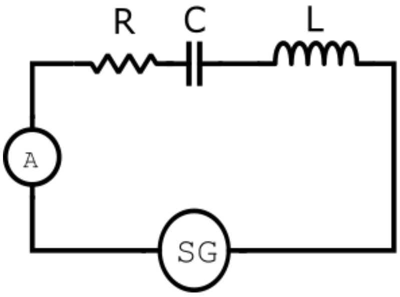

***Fig 4**. Series RLC circuit schematic*

2. The signal generator is connected to the circuit by connecting the red wire to the circuit input and the black wire to the circuit output, and the ammeter is connected in series to the circuit.
3. The I_{rms} flowing in the circuit will be read on the ammeter, and the inductor V_{rms} will be visible on the oscilloscope. Measurement of circuit current and inductor voltage is measured by changing the resistor's resistance value at one frequency value.
4. The value of the circuit current (*I*) and inductor voltage (*V*) is plotted to produce a linear equation graph that has an equation:

$$V = mI + c \tag{4}$$

   m represents the inductive reactance. By using equation (4), the inductive reactance value can be determined.

5. The inductive reactance value is used to determine the inductance of the inductor using equation (2)
6. Repeat steps 3 – 5 by changing the frequency value of the generator signal and plotting the inductance graph against the generator signal frequency.

Inductance Measurement with LC Resonance Method

The tools and materials used to measure inductance with the LC resonance method are capacitors, inductors, arbitrary frequency generators (AFG), and oscilloscopes. The series RLC circuit arrangement can be seen in Figure 5.

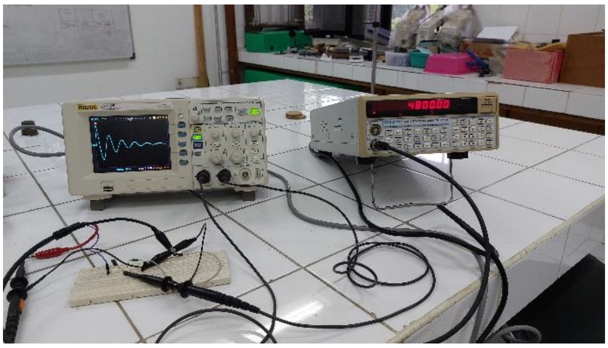

***Fig 5.** Resonance LC circuit arrangement*

The steps for measuring inductance with the LC resonance method are as follows:

1. The schematic of the LC resonance circuit used in this study is shown in Figure 6.

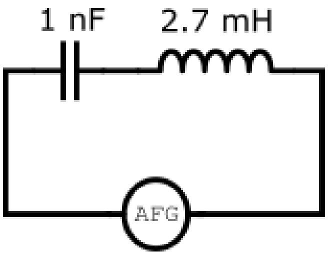

***Fig 6.** Schematic of the LC Resonance circuit*

2. The positive pole of the AFG and the oscilloscope probe in the form of a hook are connected to the input of the circuit, the negative pole of the AFG is connected to the output of the circuit, and the oscilloscope probe in the form of a crocodile claw is connected between the capacitor and inductor legs.
3. The waves in the AFG are converted into square waves, and the frequency is adjusted so that the oscilloscope shows the voltage versus time curve in the form of damped oscillations, as shown in Figure 7.

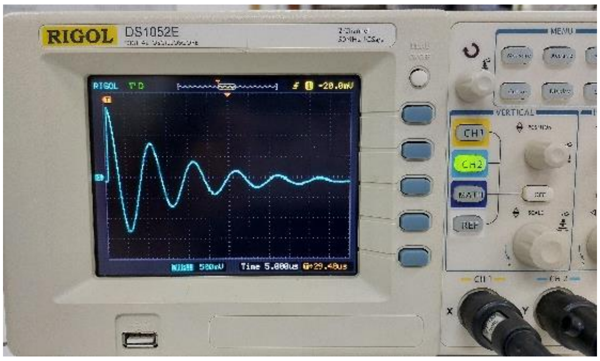

***Fig 7.** The time-voltage curve in an LC circuit*

4. The resonant frequency can be measured by specifying the period on the voltage-time curve and pressing the cursor button to display the cursor. Place the first cursor at the starting point of the sine wave and the second cursor at the endpoint of the sine wave. The frequency value is visible on the oscilloscope screen, as shown in Figure 8.

Fig 8. *The resonant frequency of the LC Resonance method*

5. Repeat steps 3 – 4 using different capacitor values. The resonant frequency and capacitance of the capacitor will be plotted to produce a linear graph whose equation is equation (4), where y interprets, m interprets, and x interprets. Knowing the linear graph's gradient value can determine the inductance value.

RESULTS AND DISCUSSIONS

Measurement with LCR meters

Measurement with an LCR meter is a direct measurement of the inductance value. This study uses two types of LCR meters: benchtop and handheld LCR meters. LCR meters have frequency settings, so the frequency value can be changed depending on the component's value to be measured. Based on recommendations from the LCR meter manual, inductors with 1 mH to 1 H are measured using a frequency of 1 kHz. So that in inductor measurements using either a benchtop or handheld LCR meter, both use a frequency of 1 kHz.

(a)

(b)

Fig 10. *Results of inductance measurements using an (a) benchtop LCR meter, (b) handheld LCR meter*

A commercial inductor with an inductance of (2.7±10%) mH is measured with ten repetitions. The inductance value measured using a benchtop LCR meter produces an average inductance value of 2.9 mH with an error percentage of 7.4%. In comparison, the inductance value measured using a handheld LCR meter produces an average inductance value of 2.7 mH with an error percentage of 0%. The measurement results with both types of LCR meters are still within the tolerance range of this commercial inductor.

Measurement with series the RLC method

As explained in the methods section, the prerequisite for determining inductance using the series RLC method is to make the circuit inductive. To meet these requirements, this study tracks the frequency value by determining the inductance value for each change in the frequency of the generator signal, then the results will be plotted on the inductance frequency graph. The results of commercial inductance measurements L = (2.7 ± 10%) mH to the frequency are shown in Figure 9. At the PLN frequency, which is 50 Hz, the inductance value obtained is around 7.0 mH; this is very far from the actual value. When the frequency of the signal generator is increased, the value of the inductance decreases and approaches its actual value. Figure 9 shows that at a frequency of 2500 Hz, the inductance value is 3.0 mH. This value does not change until the frequency is 3000 Hz. The 2500 Hz – 3000 Hz frequency is close to the value of the circuit's resonant frequency. Based on equation (3) calculations, the resonant frequency value is around 3000 Hz. If the frequency source is enlarged beyond its resonant frequency value, the resulting inductance value is far from its actual value.

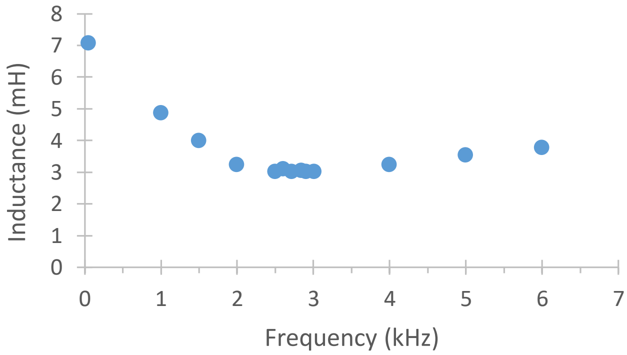

Fig 9. *Graph of inductance to the frequency with the series RLC method*

The inductance measurement using the series RLC method is carried out by plotting the value of the circuit current (*I*) and voltage of the inductor (*V*) on a cartesian diagram so that a graph is obtained, as shown in Figure 11. The resulting straight-line equation is $V = 47.204\, I + 0.033$. Based on equation (4) gradient on the inductor voltage graph to the circuit current is the inductive reactance of the circuit, so it is known that the inductive reactance of the series RLC circuit is 47.204 Ω. Using equation (2) the inductance value is 3.0 mH.

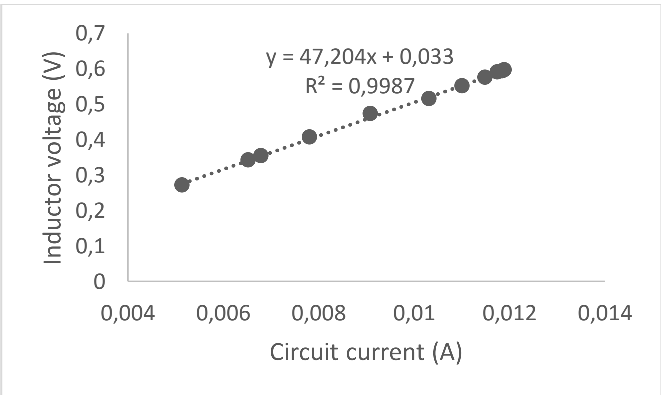

Fig 11. *Graph of inductor voltage to circuit current at a generator signal frequency of 2500 Hz*

Measurement with LC resonance method

Inductance measurements using the LC resonance method were carried out five times by varying the value of the capacitor in the circuit. The squared value of the resonant frequency for each change in the capacitor is plotted against $\frac{1}{C}$ value on the Cartesian diagram, as shown in Figure 12. The straight-line equation on the graph is expressed as $f^2 = 9.1052/C + 2 \times 10^8$. The gradient of the equation is equal to $\frac{1}{4\pi^2 L}$ so that the inductance value generated using this method is 2.7 mH with an error percentage of 0%. Measurements using this method also require a longer time when compared to using an LCR meter, but this method is more accurate and accessible than the serial RLC method.

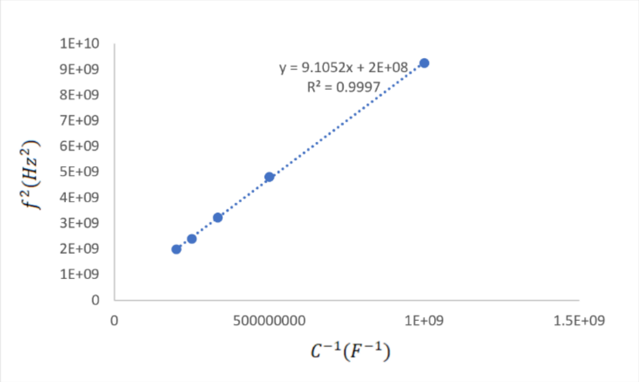

Fig 12. *Graph of* f^2 *to* $\frac{1}{C}$

Inductance measurement results of various methods

The inductance value of the measurement results with various methods can be seen in Table 1. The measurement error percentage is calculated using equation (5). Based on Table 1, the inductance value with the most remarkable error percentage results from measurements using the series RLC method. The inductance values result from measurements with a benchtop LCR meter. In comparison, the inductance value with the lowest percentage is obtained from measurements with a handheld LCR meter and the LC resonance method.

$$\text{Error percentage} = \left|\frac{\text{measurement value} - \text{actual value}}{\text{actual value}}\right| \times 100\% \quad (5)$$

Table 1. Measurements by various methods for inductors L = (2.7±10%) mH

Method	The inductance of inductor (mH)	% error
Benchtop LCR meter	2.9	7.4%
Handheld LCR meter	2.7	0%
Series RLC	3.0	11%
LC Resonance	2.7	0%

Based on the table. 1 The percentage of measurement error using the series RLC method is the largest compared to the other three methods, which is 11%. This large percentage of error is caused when varying the frequency value of the inductance; the author does not use a value exactly as the circuit's resonant frequency value. Furthermore, the percentage of measurement error using a benchtop LCR meter is greater than using a handheld LCR meter and the LC resonance method, which is 7.4%. However, this value is still within the range of commercial inductance values.

There are some differences among these various methods. Inductance determination using a benchtop or handheld LCR meter is a direct measurement; in contrast, the inductance determination using the series RLC or LC resonance method is indirect measurement. In measurements using the series RLC method, the actual inductance should be determined at resonant frequency through the measurements of the inductor voltage and the circuit current. While the LC resonance method uses the concept of circuit resonance by finding the resonant frequency using an oscilloscope.

Advantages and disadvantages
A benchtop LCR meter provides several advantages, such as making measurements easier and faster and producing accurate inductance values, while the disadvantages of this tool are expensive and unportable therefore schools rarely have this tool. A handheld LCR meter also has advantages such as easier, faster, accurate and portable in measuring inductance, while the disadvantage of handheld LCR meter with high accuracy is pretty expensive.

The use of series RLC or LC resonance method has the same advantage, that is students learn the concept of alternating current and improve their motor skills because they are required to be able to use the tools and assemble them appropriately. The LC resonance method is more accurate than the serial RLC method since the LC resonance method uses less step for inductance determination. The disadvantages of the series RLC and LC resonance methods are the needs more tools and components, more steps and longer time than measuring inductance using an LCR meter.

CONCLUSION AND SUGGESTION

The inductance of the inductor can be measured in several ways, such as using a benchtop and handheld LCR meter equipped with a frequency setting, the LC resonance method, and the RLC circuit. Measurements still within the inductor tolerance limit (≤10%) are measurements with a benchtop LCR meter with an error percentage of 7.4%, a handheld LCR meter with an error percentage of 0%, and the LC resonance method, which also produces an error percentage of 0%. For measurements using the RLC series method, the error percentage produced is 11%. This value slightly exceeds the tolerance limit of commercial inductors, and this is because the frequency of the signal generator used is not the same as the resonant frequency of the circuit. Based on the measurement steps taken, inductance measurement with an LCR meter is easier and faster because the inductance value can be immediately known, measurements with the LC resonance method produce the correct value, and the measurement steps are faster when compared to the series RLC method. However, the series RLC and LC resonance methods are perfect for school practicum activities. The accuracy of measurements using an LCR meter is highly dependent on the condition of the tool used, the level of accuracy, and skills in using the measuring tool. To produce precise measurements using a handheld LCR meter, it is recommended to use an LCR meter whose specifications are the same as or above the specifications of the LCR meter used in this study. The signal generator frequency greatly influences the measurement accuracy with the serial RLC method.

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