

University of Technology, Sydney Faculty of Engineering and Information Technology

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Assessment Number:	1
Assessment Title:	Lab 1 – Flux Linkage and Inductance
Tutorial Group:	
Students Name(s) and N	fumber(s)

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Lab work	/3
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Assessment Submission Receipt

Assesment Title:	Lab 1 – Flux Linkage and Inductance
Student's Name:	
Date Submitted:	
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Lab 1 – Flux Linkage and Inductance

Flux paths. Flux linkage. Inductance.

Introduction

The classical theory of electromagnetism relies on the imaginary concept of flux – something emanating from a source and streaming throughout all of space. It was the best concept that 19th century scientists could use to describe various "action-at-a-distance" electromagnetic phenomena. Also, the mathematics to describe phenomena involving flux was already developed because it is analogous to a normal fluid (such as water).

Today we know that electromagnetism can be put into an entirely new framework involving the special theory of relativity (and other modern theories which have special relativity as a "special" case). However, the original concept of flux is still valid, as the theory matches experimental observations to a high degree of precision. The concept of flux (and flux linkage) provides us with a way of imagining how electromagnetic phenomena work – without delving into intricate mathematics. We can "measure" flux, "draw" flux and "calculate" flux – so it is still a useful concept for engineers to use.

When the amount of flux which "links" another circuit changes, a voltage is induced. This is Faraday's Law, and we will use this law to "measure" the flux generated by a wire that links with another circuit.

Objectives

- 1. To measure the flux linkage between a small coil and a current loop in air, and hence to calculate the mutual inductance.
- 2. To determine the self inductance of a long solenoid, with both an air core and a ferromagnetic core.
- 3. To examine the effect of loop topology on flux linkage and induced voltage.

Equipment

- 1 Digital Storage Oscilloscope (DSO) Hewlett Packard HP54621A
- 1 single-phase 240 V, 8A autotransformer Warburton Franki Variac,
- 1 600 turn current transformer, 250 VA, 50Hz Berco Windavolt
- 1 function generator (FG) GFG-8016G or GFG-8020G or GFG-8016D
- 1 digital multimeter GW GDM-8045G or GW GDM-8135
- 1 clip-on power quality clamp meter Fluke 345
- Flexible welding cable loop
- 1 air-cored solenoid Oliver
- 1 mild steel cylindrical core
- 1 search coil (15 turns each)
- 1 magnetic compass

Safety

Cat. A lab

This is a Category A laboratory experiment. Please adhere to the Category A safety guidelines (issued separately).

Theory

Finding the Inductance of a Solenoid (L_1)

Method 1 – Solenoid Electric Circuit Quantities

By assuming an equivalent circuit for the solenoid, we can obtain the inductance from circuit measurements. Since we are exciting the circuit with a sinusoidal supply, phasor analysis and the concept of impedance applies:

$$\left|\mathbf{Z}_{1}\right| = \frac{\left|\mathbf{V}_{1}\right|}{\left|\mathbf{I}_{1}\right|} = \sqrt{R_{1}^{2} + \omega^{2}L_{1}^{2}} \tag{L1.1}$$

Rearranging, we get:

$$L_{1} = \frac{1}{\omega} \sqrt{\left(\frac{|\mathbf{V}_{1}|}{|\mathbf{I}_{1}|}\right)^{2} - R_{1}^{2}}$$
(L1.2)

Therefore we need to measure V_1 , I_1 (RMS or peak) and R_1 , and know the sinusoidal supply's frequency.

Method 2 – Geometry

The inductance of a conductor arrangement in a vacuum is a purely geometric property. Air is close to vacuum as far as magnetic fields are concerned. Therefore we should be able to derive the inductance of the solenoid from a consideration of its construction.

If we use the Law of Biot-Savart, we can derive an approximate theoretical value for the magnetic field density on the axis of the solenoid in air:

$$\mathbf{B}_1 = \boldsymbol{\mu}_0 \mathbf{H}_1 = \frac{\boldsymbol{\mu}_0 N_1 \boldsymbol{i}_1}{\sqrt{d^2 + l^2}} \hat{\mathbf{h}}$$
(L1.3)

If this flux density is assumed to be the same throughout the interior of the solenoid (*how valid is this assumption*?), then the flux streaming through the interior of the solenoid and linking the solenoid's turns is:

$$\phi_{av} = \int_{A} \mathbf{B}_{1} \cdot d\mathbf{A} = \frac{\mu_{0} A_{1} N_{1} \dot{l}_{1}}{\sqrt{d_{1}^{2} + l_{1}^{2}}}$$
(L1.4)

Since there are N_1 turns, then the total flux linkage must be:

$$\lambda_{11} = N_1 \phi_{av} = \frac{\mu_0 A_1 N_1^2 i_1}{\sqrt{d_1^2 + l_1^2}}$$
(L1.5)

The inductance must then be:

$$L_{1} = \frac{\lambda_{11}}{i_{1}} = \frac{\mu_{0}A_{1}N_{1}^{2}}{\sqrt{d_{1}^{2} + l_{1}^{2}}}$$
(L1.6)

Therefore, measurement of the solenoid length l_1 , diameter d_1 and number of turns N_1 is all that is required.

Pre-Lab Work [2 marks]

Flux Linkage and Mutual Inductance

1. A point *P* is at a perpendicular distance *R* from a long straight conductor carrying current i_1 :





The magnitude of the magnetic field intensity at the point P is:

H =

2. The direction of the magnetic field intensity at the point *P* is:



3. The magnitude of the magnetic flux density at the point P is:

B =

4. The direction of the magnetic flux density at the point P is:

$$\hat{\mathbf{B}} =$$

5. A rectangular coil of N_2 turns is placed in a plane containing the wire as shown below:



Figure L1.2

The magnetic flux linking the coil is:

 $\phi_{21} =$

6. The total flux linkage is:

 $\lambda_{21} =$

7. If the current i_1 is sinusoidal, $i_1 = \hat{I}_1 \sin(\omega t)$, where $\omega = 2\pi f$, then the voltage induced in the coil is:

 $v_2 =$

8. The mutual inductance between the coil and the current carrying conductor is:

 $L_{21} =$

9. An alternative derivation for the voltage induced in the coil (based on L_{21}) if the current i_1 is sinusoidal is:

 $v_2 =$

Self Inductance

 The magnetic field intensity on the axis of a long solenoid of length *l* and internal diameter *d*, where *l* >> *d*, having N₁ turns and carrying a current *i_i*, is:

2. If the core of the solenoid has a relative permeability of μ_r , then the magnitude of the magnetic flux density on the axis of a long solenoid is:

B =

3. If the flux density is assumed to be the same throughout the interior of the solenoid (*how valid is this assumption*?), then the flux streaming through the interior of the solenoid and linking the solenoid's turns is:

$$\phi_{av} =$$

4. The total flux linkage is:

$$\lambda_{11} =$$

5. The inductance of the solenoid is:



6. The inductance of a solenoid of length 800 mm, internal diameter 40 mm, 11,000 turns, with an air core, is approximately:

 $L_{1} =$

7. The impedance of an inductor L in series with a resistor R at a frequency $\omega = 2\pi f$ is:

Z =

8. The magnitude of this impedance is:

|Z| =

9. If a sinusoidal voltage of RMS amplitude V is applied across a series *RL* circuit, and the RMS current amplitude is I, then the magnitude of the impedance seen by the source is:

|Z| =

10. Hence the reactance in terms of the voltage, current, and resistance is:

X =

11. The inductance is:

L =

12. If a sinusoidal voltage of RMS amplitude 10 V and frequency 100 Hz is applied across an inductor of inductance 250 mH and winding resistance 100 Ω , then the RMS current amplitude is:

I =

13. The stored energy is:

E =

Lab Work [3 marks]

Flux Linkage and Mutual Inductance

1. Your bench is provided with a cable carrying a sinusoidal current of 100 A RMS at 50 Hz as shown in Figure L1.3 below (check the actual current on the clip-on ammeter).





- Using a long 4 mm connecting lead, form a rectangular loop of 1 turn with two sides parallel to the cable. The loop is to be 600 mm long, 200 mm wide, and placed 100 mm from the cable. Use sticky tape to keep the sides straight and in position.
- 3. Connect the loop to Channel 1 of the DSO (via the Ch 1 coaxial lead).
- 4. Turn the DSO on.
- In the File section, press the Save-Recall button, then choose the softkey Default Setup. This will ensure the DSO is in a known state, e.g. all probe ratios are restored to 1:1, trigger set to Ch 1, etc.
- 6. In the Waveform section, push the Acquire key and choose Averaging to reduce the noise on the display.
- 7. Set the Time / div to 5.00 ms and the Volts / div to 1 or 2 mV / div.

- 8. In the Trigger section, press the Edge button and choose Ext and then Line to trigger the DSO from it's 50 Hz AC supply.
- 9. Draw the coil, showing dimensions and distance from the cable:



10. Accurately sketch the waveform of the induced voltage in the coil, noting both horizontal and vertical scales.



11. From the DSO display, estimate the peak voltage of the fundamental component of the induced voltage:

 $\hat{V} =$

Induced voltage waveform

12. From the cable current, coil dimensions, and number of turns, the flux linkage of the coil is *calculated* as:

 $\lambda_{21} =$

13. The mutual inductance between the coil and the current carrying conductor is *calculated* as:

 $L_{21} =$

- 14. Thus, the peak voltage induced in the coil is *calculated* to be:
 - $\hat{V} =$
- 15. Compare the peak of the fundamental component of the *observed* voltage (part 9) with the *calculated* peak voltage (part 12).

Comment:

16. Place a single twist in the centre of the coil as in Figure L1.4:



Figure L1.4

17. From the DSO display, estimate the peak voltage of the fundamental component of the induced voltage:

 $\hat{V} =$

 From the cable current, coil dimensions, and number of turns, the flux linkage of the coil is *calculated* as:

 $\lambda_{21} =$

19. Explain the results of parts 17 and 18:

Explain:			

20. Increase the number of turns in the coil to two. Keep the coil dimensions the same:



Figure L1.5

21. From the DSO display, estimate the peak voltage of the fundamental component of the induced voltage:

$$\hat{V} =$$

22. Explain the result of part 21:

Explain:

23. You may also try more turns, more coil area, and more twists as time allows. Note the results.

Self Inductance

In this part of the experiment the inductance of the long wire wound solenoid is determined by first measuring its resistance, then its AC impedance, and then calculating the inductance.

1. Use a digital multimeter to measure the solenoid resistance, R:

R =

- 2. Connect the function generator to the solenoid. Set the function generator to a 100 Hz sine wave, minimum output voltage.
- 3. Connect the digital multimeter in series with the solenoid, using terminals and settings so that it reads the AC RMS current through the solenoid.

Sketch the circuit diagram:

4. Adjust the function generator to give about 20 mA RMS current in the solenoid. Note the exact current:

I =

5. Without changing the function generator setting, reconnect the digital multimeter in parallel with the solenoid so that it reads the AC RMS voltage across the solenoid.

Sketch the circuit diagram:

6. Record the voltage across the solenoid:

$$V =$$

7. Calculate the solenoid impedance magnitude from the voltage and current measurements:

$$\left|\mathbf{Z}\right| = \frac{V}{I} =$$

8. Using the values of |Z| and *R*, calculate the inductance of the solenoid:

$$X = L =$$

9. Measure the solenoid length l, internal diameter d_i , outside diameter d_o , and note the number of turns N:

l =			
$d_i =$			
$d_o =$			
N =			

10. Calculate the average diameter of the solenoid:

$$d = \frac{d_i + d_o}{2} =$$

11. Using the average of the internal and external diameters, calculate the solenoid inductance:

L =

12. Compare the measured inductance (part 8) with the calculated inductance (part 11) and comment:

Comment:

13. Introduce the iron core into the solenoid slowly. Observe the change on the current. What is the effect on the self inductance?

Explain:		

Search Coils (if time permits)

- 1. Slide a search coil over the end of the solenoid and slide it to the centre of the solenoid.
- 2. Connect Channel 1 of the DSO to the solenoid, and Channel 2 to the search coil.
- 3. Set the DSO to trigger off Channel 1.

- 4. Remove the iron rod from the solenoid.
- 5. Apply sinusoidal, square and triangular voltage waveforms to the solenoid, and observe the induced voltage waveform on the search coil.
- 6. Record and briefly explain the results (take note of the phase relationship between the solenoid voltage and the search coil voltage):

- 7. Insert the iron rod into the solenoid.
- 8. Apply sinusoidal, square and triangular voltage waveforms to the solenoid, and observe the induced voltage waveform on the search coil.
- 9. Record and briefly explain some typical results (take note of the phase relationship between the solenoid voltage and the search coil voltage):

Report

Only submit <u>ONE</u> report per lab group.

Complete the assignment cover sheet.

Ensure you have completed:

- 1. <u>Pre-Lab Work</u> calculations and explanations where required.
- 2. <u>Lab Work</u> waveforms, readings, calculations, explanations.

<u>The lab report is due in exactly two (2) weeks.</u> <u>You should hand the report directly to your tutor.</u>