Study of Lock-in Amplifier

Gayatri P
3rd year, Integrated M.Sc. Physics
Roll No.: 2211185
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This experiment used a Lock-In Amplifier to measure low resistance and mutual inductance amidst noise. Proper calibration highlighted its precision in detecting small signals and isolating them effectively, demonstrating its capability to provide accurate measurements despite external interference.

I. OBJECTIVE

1. Study and Calibration of the Lock-in Amplifier using a voltage divider circuit.
2. Measurement of Mutual Inductance of two coils using the Lock-in Amplifier.
3. Measurement of low resistance with the help of the Lock-in Amplifier.

II. THEORY

The lock-in amplifier is a device, which can measure very small AC voltages in the presence of noise. It uses the principle of phase sensitive detection. It produces a maximum DC output when the signal to be measured is in phase with a reference signal at the same frequency. The lock-in amplifier using AD630 chip is low cost and for the teaching purpose of phase sensitive detection. It has limited frequency and input voltage ranges of about frequency range 200 Hz to 2 kHz and input voltages of few microvolts.

Theoretical Considerations

Amplifiers typically operate with a bandwidth spanning several kilohertz, and they are subject to various sources of noise. One common type is flicker noise, which is present in all electronic instruments and has a power spectrum that inversely varies with frequency. This noise becomes problematic primarily at very low frequencies. Another source of noise originates from electromagnetic interference, such as that produced by running motors, fluorescent lights, and similar devices. This type of noise exhibits a peak in its power spectrum at the specific frequency of the interfering source, like the motor or mains frequency, and can be mitigated using electromagnetic shielding.

A third significant source of noise is thermal noise, which is thermodynamic in origin and unavoidable. Its power spectrum extends across all frequencies, earning it the name "white noise". In a circuit with a resistance R through which a current I flows, the voltage across the resistance fluctuates randomly around the average value $V_0 = IR$. The mean square fluctuation of the voltage, denoted as $\langle (V - V_0)^2 \rangle$, is calculated over a long time period. If this noise is measured over a bandwidth W, the mean square voltage is given by:

$$\langle (V - V_0)^2 \rangle = 4k_B TRW \tag{1}$$

where k_B is the Boltzmann constant, and T is the temperature.

To minimize thermal noise, one can either reduce the temperature T or decrease the bandwidth W of the amplifier. When detecting very weak signals at room temperature, it is often necessary to effectively reduce the bandwidth to just a few Hertz, despite the amplifier's typical kilohertz range. This reduction is achieved using a technique known as Phase Sensitive Detection.

Consider an AC sinusoidal signal, such as the current through the primary coil of a mutual inductance or a periodically modulated light signal. The resulting effect, such as the induced emf in the secondary coil, will have the same frequency as the cause but may differ in phase. For example, the induced emf will be $\pi/2$ out of phase with the current in the primary coil but will share its frequency. This effect is often weak, in the range of microvolts or nanovolts. Amplifying this weak signal directly also amplifies noise, which can overwhelm the signal, especially in an amplifier with a wide frequency range. To overcome this noise and enhance the weak signal, a reference signal in phase with the cause is used. Thus we can write

$$V_{\text{signal}} = V_0 \sin(\omega t + \phi) \tag{2}$$

$$V_{\text{ref}} = V_0 \sin(\omega t) \tag{3}$$

Let's consider the magnitudes of the signal and reference voltage after amplification in our circuit. These signals are then fed into the AD 630 chip, a phasesensitive detector. This chip contains two identical amplifiers: a noninverting amplifier, where the output is in phase with the input, and an inverting amplifier, where the output is 180° out of phase with the input.

A comparator within the chip operates a switch based on the reference signal. The comparator's rapid response time, combined with the high slew rate and fast settling of the amplifiers, minimizes switching distortion. When the reference signal is positive (during $0 < t < T/2$),

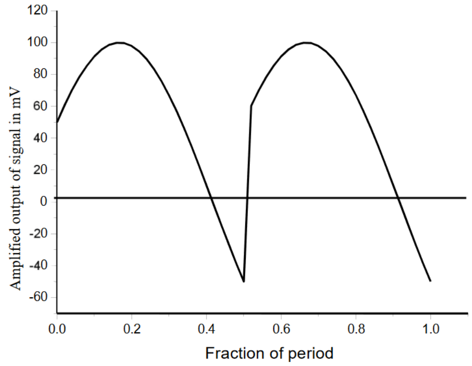


FIG. 1: Amplified output V_{out} when the reference signal is fed to the comparator.

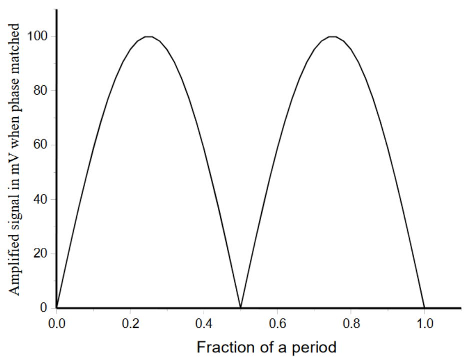


FIG. 2: Amplified output signal when the reference signal is phase Shifted by ϕ and fed to AD630 chip

the comparator directs the weak signal Vsignal to the noninverting amplifier, producing an output

$$V_{\text{out}} = \mu V_{\text{signal}}, \text{ for } 0 < t < T/2 \tag{4}$$

When the reference signal is negative (during $T/2 < t < T$), the weak signal is routed to the inverting amplifier, resulting in an output:

$$V_{\text{out}} = -\mu V_{\text{signal}}, \text{ for } T/2 < t < T \tag{5}$$

As shown in Figure 1, the output signal is positive for most of the period, with a small negative portion. This results in an output signal that includes both an average DC component and an AC component at frequencies ω, 2ω, and higher harmonics. By using a filter that shunts the AC components to ground, the DC output having a voltage V_{dc} can be isolated.

The DC output can be calculated using the equation:

$$V_{dc} = \frac{1}{T}\int_0^{T/2} \mu V_0 \sin(\omega t + \phi)\, dt - \frac{1}{T}\int_{T/2}^{T} \mu V_0 \sin(\omega t + \phi)\, dt \tag{6}$$

Simplifying this, and putting $\omega T = 2\pi$,

$$V_{dc} = \frac{4\mu V_0}{2\pi} \cos\phi \tag{7}$$

By introducing a phase-shift circuit for the reference signal before sending it to the comparator in the AD 630, the output DC voltage will change as the phase shift increases from zero. The DC voltage peaks when the reference signal is phase-shifted by ϕ, aligning it in phase with the weak signal V_{signal}. At this point, the output voltage resembles that shown in Figure 2, and the average DC voltage V_{dc} reaches its maximum value of $2\mu V_0/\pi$. This technique is called phase-sensitive detection, and the amplifier is known as a lock-in amplifier because it locks the weak signal in phase with the phase-shifted reference to maximize the DC output voltage. By measuring the phase shift needed to achieve this maximum output on an oscilloscope, we can determine the phase difference between the effect and the cause.

If there is noise at a frequency ω' different from the reference frequency ω, using a large integration time (much longer than the reference signal's period) significantly reduces its contribution to V_{dc}. Only noise frequencies close to ω, differing by n/τ (where n is a small number and τ is the integration time), contribute to V_{dc}. Therefore, the effective bandwidth of the lock-in amplifier is n/τ. For an integration time of 1 second, the bandwidth W is a few Hz, effectively suppressing thermal and other noise.

Measurement of Mutual Inductance

When two coils are placed side by side and an AC current flows through one coil (the primary), an AC voltage of the same frequency is induced in the other coil (the secondary). If the primary current varies as

$$I = I_0 \sin(s\pi f t) \tag{8}$$

where f is the frequency in Hertz and the emf induced in the secondary coil is given by

$$V = -M\frac{dI}{dt} = -2\pi M f I_0 \sin\left(2\pi f t + \frac{\pi}{2}\right) \tag{9}$$

From this, we observe that

- The phase difference between the primary current and the induced emf is $\pi/2$.
- The induced emf is proportional to the amplitude I_0 of the primary current.
- The induced emf is also proportional to the frequency f.

We first plot the DC output of the Lock in Amplifier at different frequencies. Each plot is a straight line. The intercept of the line increases with an increase in frequency.

Now plot the slopes at different frequencies along with the frequency. The slope of this plot is given by

$$\beta = \frac{2\pi M \mu}{R} \tag{10}$$

where μ is the amplification of Lock-in Amplifier and R is the resistance of the primary circuit. Knowing R and μ we can get M.

Measurement of Low Resistance

Measurement of low resistance (resistance less than an Ohm) with the DC technique would require a high current. Also since the voltage developed across the resistance will be small, it will be affected by broadband noise when it is amplified.

If we plot the graph between V_{dc} and V_{ac} then the slope is given by $\frac{dV_{dc}}{dV_{ac}}$. Now,

$$dV_{ac} = R\, dI_{ac} \tag{11}$$

where R is the total resistance in the primary circuit and dI_{ac} is the change in the current through the low resistance as the voltage changes by dV_{ac}. The output V_{dc} is proportional to the voltage V_r across the low resistance r. When the current through the low resistance is changed by dI_{ac}, the voltage V_r changes by dV_r,

$$dV_r = r\, dI_{ac} \tag{12}$$

$$\implies dV_{dc} = \mu dV_r = \mu r\, dI_{ac} = \frac{\mu r}{R} dV_{ac} \tag{13}$$

$$\implies \frac{dV_{dc}}{dV_{ac}} = \frac{\mu r}{R} \tag{14}$$

III. EXPERIMENTAL SETUP

Apparatus

1. Lock-in amplifier
2. Oscilloscope
3. Breadboard and connecting wires
4. Function Generator
5. Test low resistance
6. Resistances
7. BNC cables
8. Test mutual Induction Coil
9. Digital Multimeter

IV. PROCEDURE

A. Calibration of Lock-in Amplifier

1. For calibrating the Lock-In amplifier, a voltage divider circuit using 4.7kΩ and 12Ω is created.
2. The reference is taken across former and the input signal to the amplifier is taken from the later. The DC output from the amplifier is measured using a digital multimeter.
3. The DC offset is adjusted and the phase between the two signals is set to zero using the phase nob of the amplifier.
4. For every frequency between 300 to 1500 Hz at an interval of 300 Hz values are taken (Table 1 and Table 3) for two values of gain of 50 and 100.

B. Calculation of Mutual Inductance

1. For finding the mutual inductance of the input signal is taken from the secondary coil.
2. The voltage across the primary signal is taken as reference.
3. The REF and REF' are connected to oscilloscope to obtain the Lissajous figure to ensure that phase difference between them is 90 degrees as a result the reference and the signal are in phase.
4. Vary V_{ac} from 7 - 15 V and note down the values of V_{dc}.
5. V_{ac} and V_{dc} are measured for 4 sets of frequencies from 600 Hz to 1500 Hz.

C. Measurement of Low Resistance

1. With the same voltage divider circuit we used for calibration, the 4.7 kΩ is swapped with a 500 Ω resistor (across the reference).
2. The input signal to the amplifier is connected across the test resistance.
3. Vary V_{ac} from 1 - 3 V and note down the values of V_{dc}.
4. V_{ac} and V_{dc} are measured for 5 sets of frequencies from 300 Hz to 1500 Hz.

V. OBSERVATION AND CALCULATIONS

- Least count for measurement of resistance = 0.001 kΩ or 0.1 Ω
- Least count for measurement of V_{ac} (pp) = 0.01 V
- Least count for measurement of V_{dc} (RMS) = 0.001 V
- Least count for measurement of frequency = 0.001 kHz

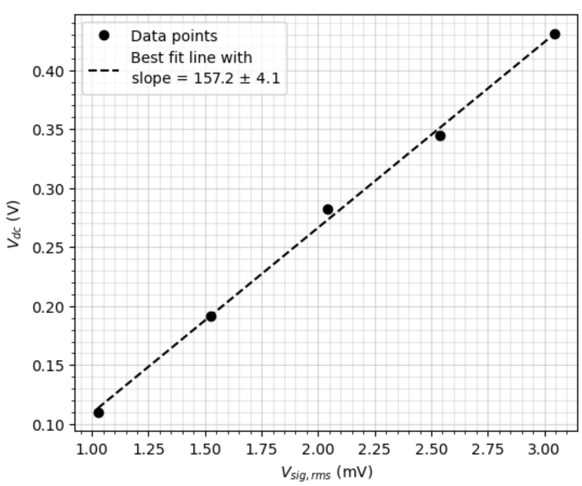
A. Calibration of Lock-in Amplifier

Here $R_1 = 4.700$ kΩ and $R_2 = 13.5$ kΩ, so

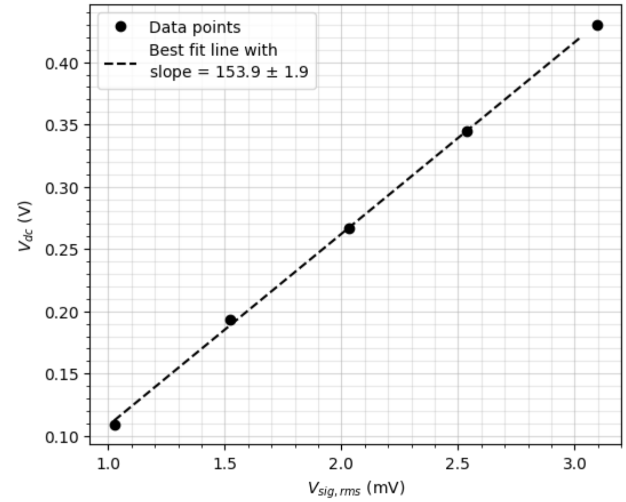
$$V_{\text{sig, rms}} = \frac{13.5}{4700} V_{\text{ac, rms}} = \frac{13.5}{4700 \cdot 2\sqrt{2}} V_{\text{ac, pp}}$$

Frequency (Hz)	V_{ac} (pp) (V)	$V_{ac,\text{rms}}$ (V)	$V_{\text{sig, rms}}$ (V)	$V_{dc,\text{rms}}$ (V)
300	1.01	0.35709	0.00103	0.110
	1.50	0.53033	0.00152	0.192
	2.01	0.71064	0.00204	0.282
	2.50	0.88388	0.00254	0.345
	3.00	1.06066	0.00305	0.431
600	1.01	0.35709	0.00103	0.109
	1.50	0.53033	0.00152	0.193
	2.00	0.70711	0.00203	0.267
	2.50	0.88388	0.00254	0.345
	3.05	1.07834	0.00310	0.430
900	1.01	0.35709	0.00103	0.109
	1.51	0.53387	0.00153	0.194
	2.01	0.71064	0.00204	0.284
	2.50	0.88388	0.00254	0.349
	3.00	1.06066	0.00305	0.441
1200	1.00	0.35355	0.00102	0.108
	1.50	0.53033	0.00152	0.194
	2.05	0.72478	0.00208	0.273
	2.50	0.88388	0.00254	0.345
	3.00	1.06066	0.00305	0.441
1500	1.00	0.35355	0.00102	0.108
	1.50	0.53033	0.00152	0.194
	2.00	0.70711	0.00203	0.267
	2.50	0.88388	0.00254	0.353
	3.00	1.06066	0.00305	0.434

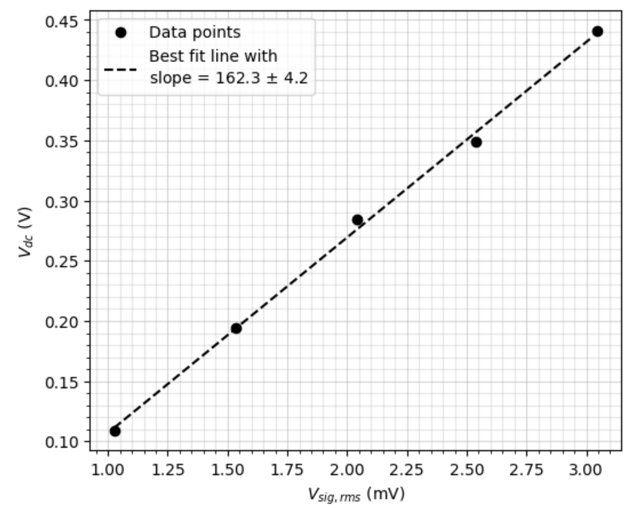
TABLE I: Data for calibration at gain 50



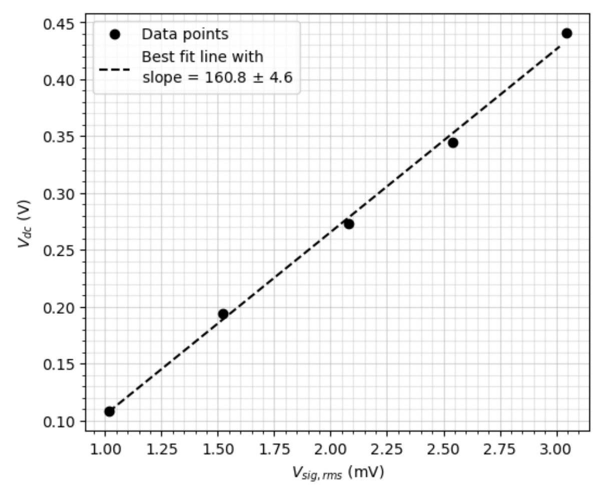
(a) 300 Hz



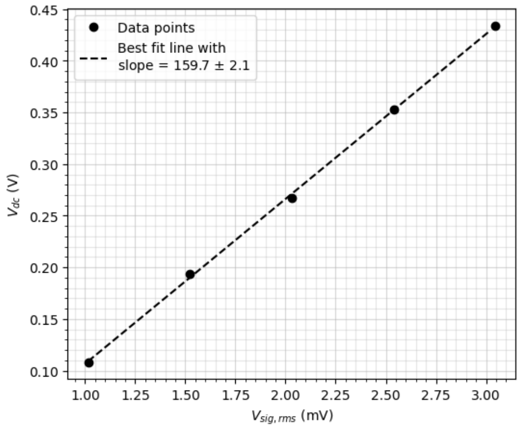
(b) 600 Hz



(c) 900 Hz



(d) 1200 Hz



(e) 1500 Hz

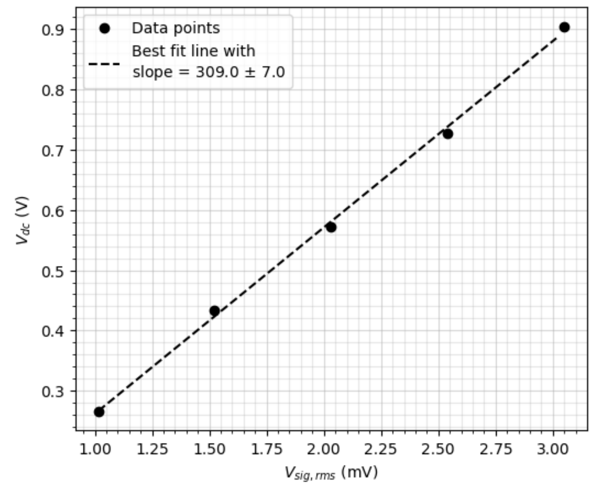
FIG. 3: Callibration curve for Gain 50 at different frequencies

f (Hz)	μ	Error ($\delta\mu$)
300	157.2	4.1
600	153.9	1.9
900	162.3	4.2
1200	160.8	4.6
1500	159.7	2.1

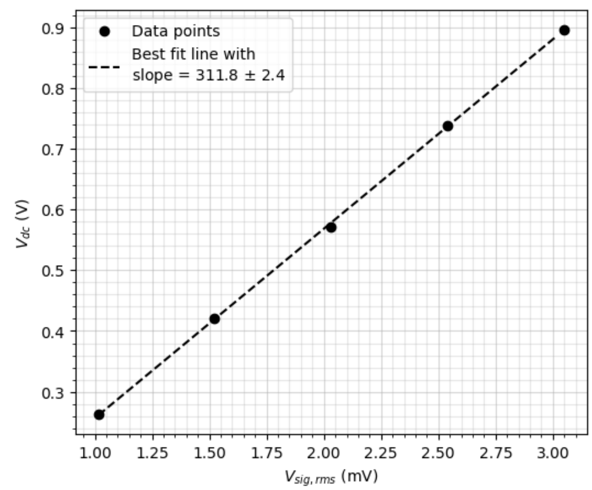
TABLE II: μ and error in μ for gain 50 from Fig. 3. Hence, the average value of μ for gain 50 is $\mu_{50} = 158.8$.

Frequency (Hz)	V_{ac} (pp) (V)	$V_{ac,\text{rms}}$ (V)	$V_{\text{sig, rms}}$ (V)	$V_{dc,\text{rms}}$ (V)
300	1.00	0.35355	0.00102	0.266
	1.50	0.53033	0.00152	0.434
	2.00	0.70711	0.00203	0.572
	2.50	0.88388	0.00254	0.727
	3.00	1.06066	0.00305	0.904
600	1.00	0.35355	0.00102	0.263
	1.50	0.53033	0.00152	0.421
	2.00	0.70711	0.00203	0.572
	2.50	0.88388	0.00254	0.738
	3.00	1.06066	0.00305	0.896
900	1.00	0.35355	0.00102	0.265
	1.50	0.53033	0.00152	0.408
	2.00	0.70711	0.00203	0.578
	2.50	0.88388	0.00254	0.723
	3.00	1.06066	0.00305	0.880
1200	1.00	0.35355	0.00102	0.264
	1.50	0.53033	0.00152	0.429
	2.00	0.70711	0.00203	0.578
	2.50	0.88388	0.00254	0.734
	3.00	1.06066	0.00305	0.901
1500	1.00	0.35355	0.00102	0.264
	1.50	0.53033	0.00152	0.428
	2.00	0.70711	0.00203	0.565
	2.50	0.88388	0.00254	0.717
	3.00	1.06066	0.00305	0.899

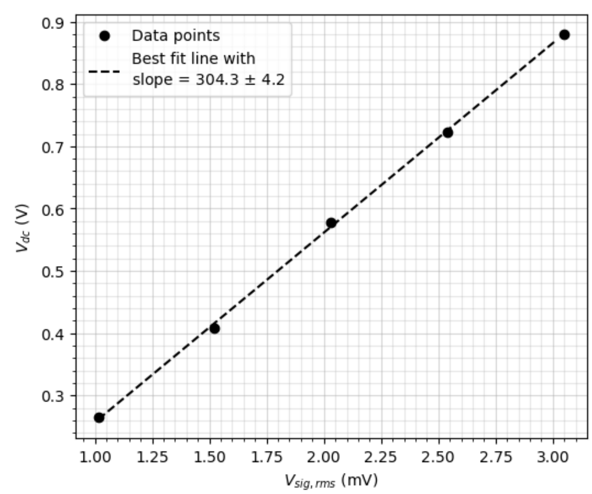
TABLE III: Data for calibration at gain 100



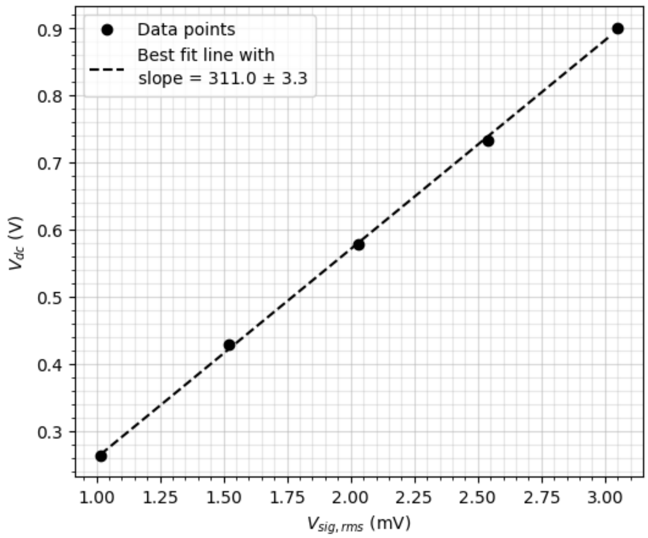
(a) 300 Hz



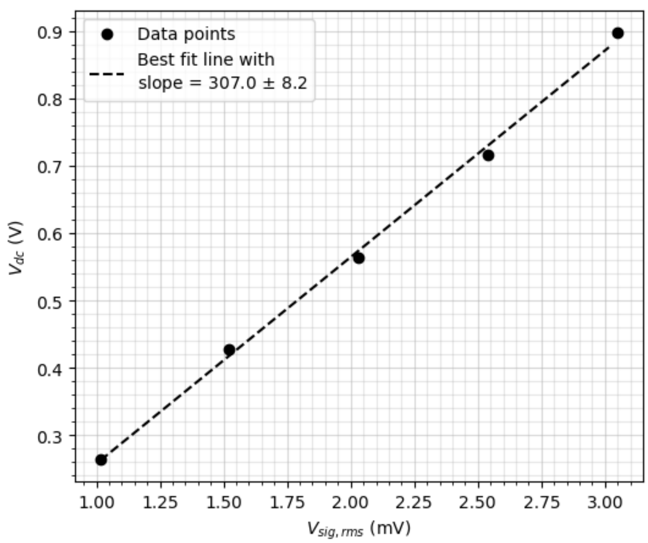
(b) 600 Hz



(c) 900 Hz



(d) 1200 Hz



(e) 1500 Hz

FIG. 4: Callibration curve for Gain 100 at different frequencies

f (Hz)	μ	Error ($\delta\mu$)
300	309.0	7.0
600	311.8	2.4
900	304.3	4.2
1200	311.0	3.3
1500	307.0	8.2

TABLE IV: μ and error in μ for gain 100 from Fig. 4. Hence, the average value of μ for gain 100 is $\mu_{100} = 308.6$.

B. Calculation of Mutual Inductance

Frequency (Hz)	V_{ac} (pp) (V)	$V_{ac,\mathrm{rms}}$ (V)	$V_{dc,\mathrm{rms}}$ (V)
600	7.00	2.47487	0.036
	9.00	3.18198	0.062
	11.00	3.88909	0.086
	13.00	4.59619	0.118
	15.00	5.30330	0.147
900	7.00	2.47487	0.072
	9.00	3.18198	0.094
	11.00	3.88909	0.141
	13.05	4.61387	0.184
	15.00	5.30330	0.223
1200	7.05	2.49255	0.126
	9.00	3.18198	0.158
	11.00	3.88909	0.229
	13.00	4.59619	0.285
	15.00	5.30330	0.344
1500	7.00	2.47487	0.154
	9.00	3.18198	0.233
	11.00	3.88909	0.299
	13.00	4.59619	0.364
	15.00	5.30330	0.439

TABLE V: Data for calculation of Mutual Induction at 100 gain

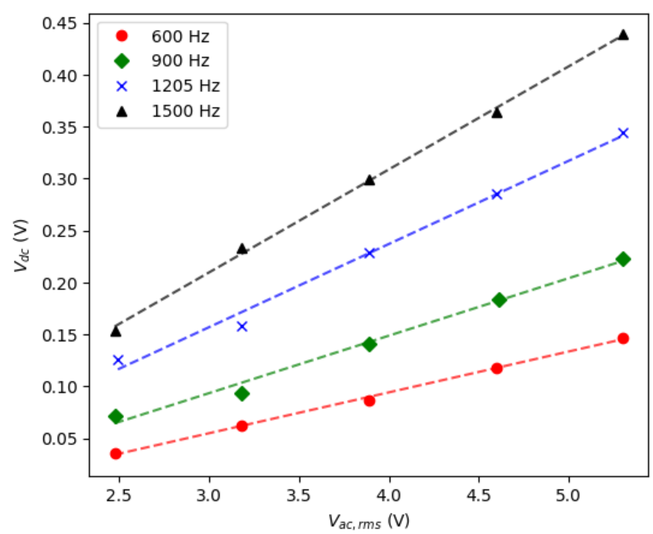


FIG. 5: V_{dc} vs V_{ac} at different frequencies for measurement of mutual induction at gain 100

Now the slope of the graph in Fig. 6, $\beta = 6.8 \times 10^{-5}$ Hz^{-1} is given by Eq. 10. Substituting the value with $R = 4.8$ kΩ,

$$M = \frac{\beta R}{2\pi\mu_{100}} = 168.3\,\mu\mathrm{H}$$

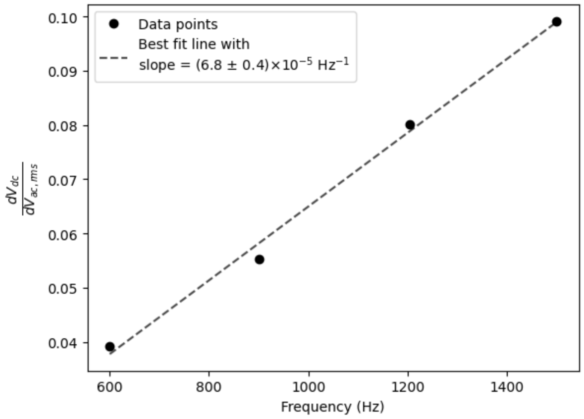


FIG. 6: $\frac{dV_{dc}}{dV_{ac}}$ vs frequency plot to calculate Mutual Inductance

C. Measurement of Low Resistance

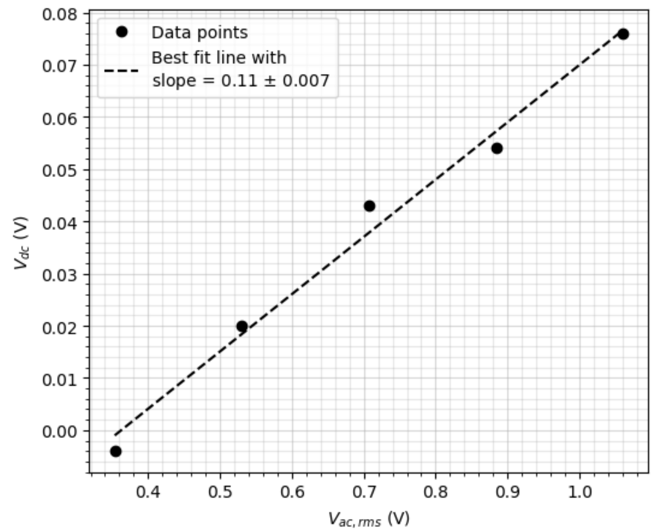
The value of Low resistance is given by

$$\text{slope } = \frac{dV_{dc}}{dV_{ac}} = \frac{\mu r}{R}$$
$$\text{where } \frac{1}{R} = \frac{1}{0.995} + \frac{1}{0.995}$$

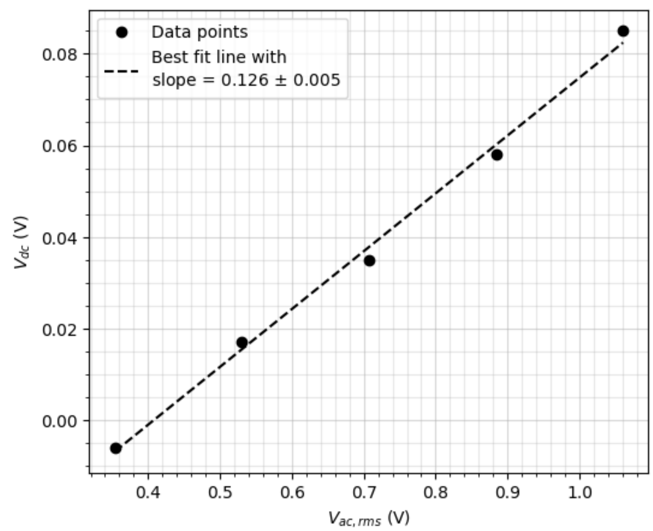
Hence, $R = 0.498$ kHz.

Frequency (Hz)	V_{ac} (pp) (V)	$V_{ac,\text{rms}}$ (V)	$V_{dc,\text{rms}}$ (V)
300	1.00	0.35355	-0.004
	1.50	0.53033	0.020
	2.00	0.70711	0.043
	2.50	0.88388	0.054
	3.00	1.06066	0.076
600	1.00	0.35355	-0.006
	1.50	0.53033	0.017
	2.00	0.70711	0.035
	2.50	0.88388	0.058
	3.00	1.06066	0.085
900	1.00	0.35355	-0.006
	1.50	0.53033	0.017
	2.00	0.70711	0.042
	2.50	0.88388	0.058
	3.00	1.06066	0.084
1200	1.00	0.35355	-0.007
	1.50	0.53033	0.017
	2.00	0.70711	0.035
	2.50	0.88388	0.058
	3.00	1.06066	0.083
1500	1.00	0.35355	-0.001
	1.50	0.53033	0.016
	2.00	0.70711	0.043
	2.50	0.88388	0.057
	3.00	1.06066	0.083

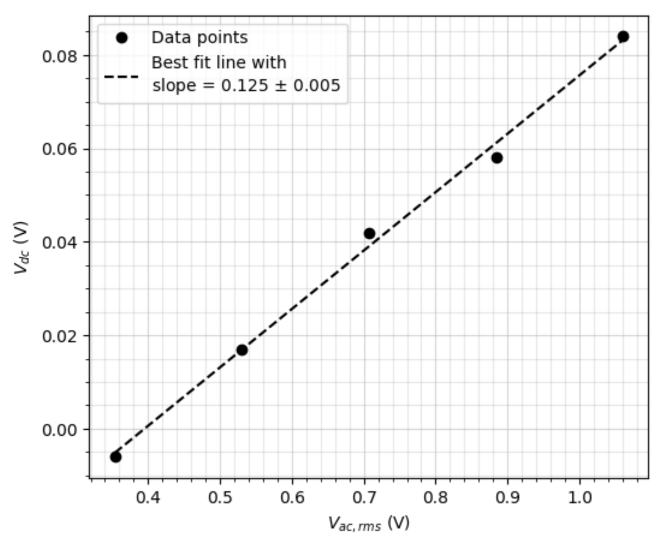
TABLE VI: Data for measurement of Low resistance at 50 gain



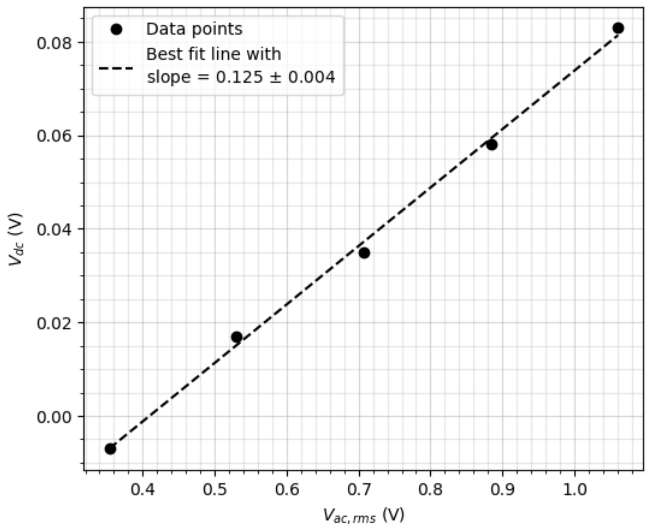
(a) 300 Hz



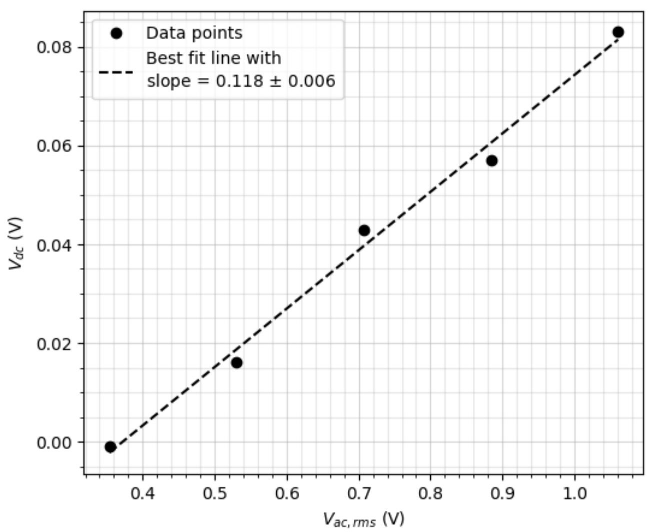
(b) 600 Hz



(c) 900 Hz



(d) 1200 Hz



(e) 1500 Hz

FIG. 7: V_{ac} vs V_{dc} plots for Gain 50 at different frequencies for measurement of low resistance

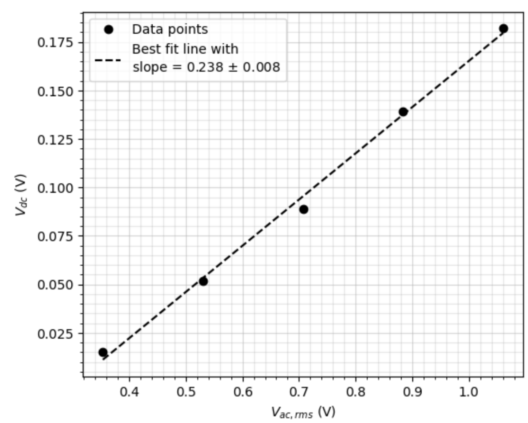
f (Hz)	slope	Error in slope	r (Ω)	δr (Ω)
300	0.110	0.007	0.344	0.023
600	0.126	0.005	0.395	0.016
900	0.125	0.005	0.392	0.015
1200	0.125	0.004	0.392	0.012
1500	0.118	0.006	0.370	0.020

TABLE VII: The slopes of plots from Fig. 7 and the calculated r values (using Eq. 14) and their corresponding error values (using Eqn. 17)

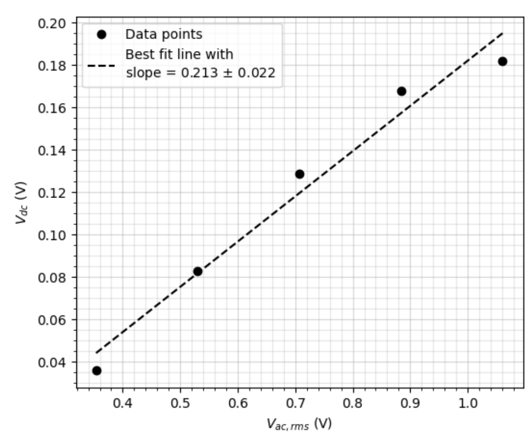
Thus the average value of r obtained here is $r_{50} = 0.382\,\Omega$.

Frequency (Hz)	V_{ac} (pp) (V)	$V_{ac,\mathrm{rms}}$ (V)	$V_{dc,\mathrm{rms}}$ (V)
300	1.00	0.35355	0.015
	1.50	0.53033	0.052
	2.00	0.70711	0.089
	2.50	0.88388	0.139
	3.00	1.06066	0.182
600	1.00	0.35355	0.036
	1.50	0.53033	0.083
	2.00	0.70711	0.129
	2.50	0.88388	0.168
	3.00	1.06066	0.182
900	1.00	0.35355	0.033
	1.50	0.53033	0.078
	2.00	0.70711	0.126
	2.50	0.88388	0.164
	3.00	1.06066	0.211
1200	1.00	0.35355	0.035
	1.50	0.53033	0.081
	2.00	0.70711	0.119
	2.50	0.88388	0.163
	3.00	1.06066	0.205
1500	1.00	0.35355	0.034
	1.50	0.53033	0.078
	2.00	0.70711	0.122
	2.50	0.88388	0.160
	3.00	1.06066	0.209

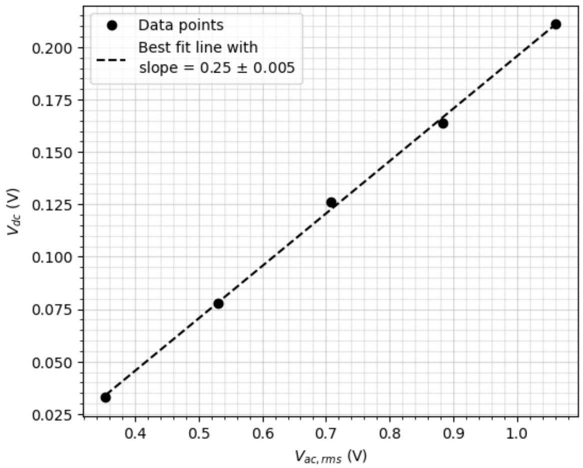
TABLE VIII: Data for measurement of Low resistance at 100 gain



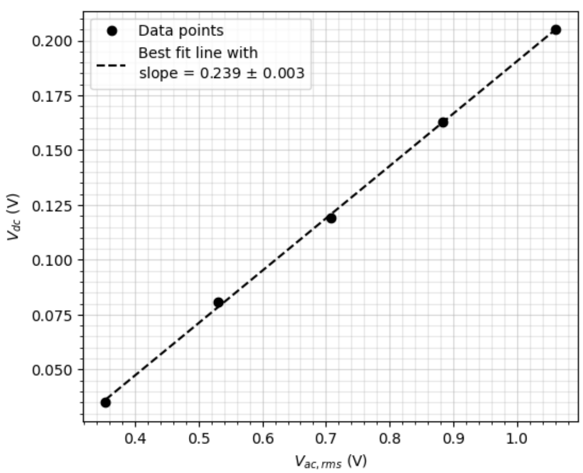
(a) 300 Hz



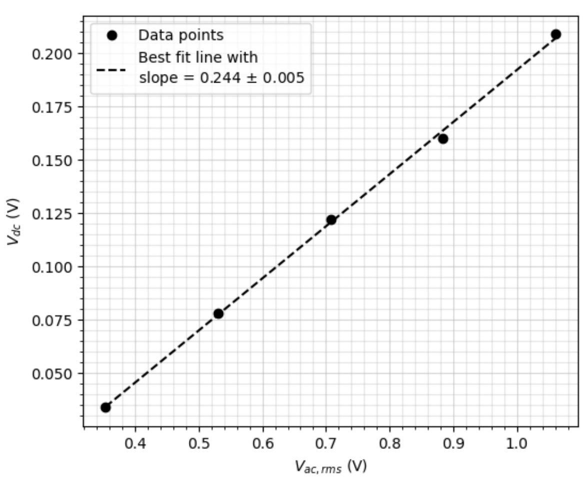
(b) 600 Hz



(c) 900 Hz



(d) 1200 Hz



(e) 1500 Hz

FIG. 8: V_{ac} vs V_{dc} plots for Gain 100 at different frequencies for measurement of low resistance

f (Hz)	slope	Error in slope	r (Ω)	δr (Ω)
300	0.238	0.008	0.384	0.015
600	0.213	0.022	0.344	0.035
900	0.250	0.005	0.403	0.010
1200	0.239	0.003	0.385	0.009
1500	0.244	0.005	0.394	0.010

TABLE IX: The slopes of plots from Fig. 8 and the calculated r values (using Eq. 14) and their corresponding error values (using Eqn. 17)

Thus the average value of r obtained here is $r_{100} = 0.379\,\Omega$. Hence the final average value comes out to be,

$$r = \frac{r_{50} + r_{100}}{2} = 0.380\,\Omega$$

VI. ERROR ANALYSIS

The calibration error is the error in the slope which is given in tables II and IV. The error in mutual inductance is given by,

$$\delta M = M\sqrt{\left(\frac{\delta\mu}{\mu}\right)^2 + \left(\frac{\delta\beta}{\beta}\right)^2 + \left(\frac{\delta R}{R}\right)^2} \tag{15}$$

where

$$\delta\mu = \frac{1}{\sqrt{5}}\sqrt{\sum_{f_i} (\mu_{f_i})^2} \tag{16}$$

for each of the 5 values of f_i in tables II and IV. This comes out to be,

- For gain 50, $\delta\mu_{50} = 3.6$
- For gain 100, $\delta\mu_{100} = 5.5$

Now using $\delta\mu_{100} = 5.5$, $\delta\beta = 0.4 \times 10^{-5}$ Hz^{-1} (from Fig. 6) and $\delta R = 0.01$ kΩ, we get $\delta M = 9.5\,\mu$H.

For the error in r, we get

$$\delta r_{f_i} = r_{f_i}\sqrt{\left(\frac{\delta\mu}{\mu}\right)^2 + \left(\frac{\delta\,\text{slope}}{\text{slope}}\right)^2 + \left(\frac{\delta R}{R}\right)^2} \tag{17}$$

Tables VII and IX show the δr for every value of r calculated using Eq. 17. The average error in r can be calculated as,

$$\delta r = \frac{1}{\sqrt{5}}\sqrt{\sum_{f_i} (r_{f_i})^2} \tag{18}$$

for each of the 5 values of f_i in. Using this the errors are $\delta r_{50} = 0.018\,\Omega$ and $\delta r_{100} = 0.019\,\Omega$ for both values of gain. Thus,

$$\delta r = \frac{1}{\sqrt{2}}\sqrt{(0.018)^2 + (0.019)^2} = 0.018\,\Omega$$

VII. RESULTS & DISCUSSION

In this experiment, we studied a Lock-in Amplifier and used it to measure quantities the Mutual Inductance and low resistance values. The results are detailed below.

Firstly, we calibrated the Lock-in Amplifier for two values of gain at 50 and 100 to find the amplification factor, which comes out to be,

$$\mu_{50} = 158.8 \pm 3.6$$
$$\mu_{100} = 308.6 \pm 5.5$$

The mutual inductance measured for the given coils comes out to be,

$$M = (168.3 \pm 9.5)\,\mu\text{H}$$

The value of low resistance measured comes out to be,

$$r = (0.380 \pm 0.018)\,\Omega$$

Hence we have found out that a lock-in amplifier plays a critical role of phase-sensitive detection in improving the signal-to-noise ratio. We can summarise the pros and cons of a lock-in amplifier as follows.

Advantages

The stability of the lockin amplifier's output in noisy environments, thanks to the phase-locked loop, highlights the lock-in amplifier's strength in rejecting noise and maintaining synchronization. This is especially useful in environments where external noise sources could otherwise interfere with measurements, ensuring reliable data acquisition.

The clear linear relationship between the induced EMF and the current through the primary coil that you observed is consistent with the theoretical model of mutual inductance. The lock-in amplifier's ability to measure this relationship accurately, even at low signal levels, demonstrates its effectiveness in detecting small signals in experiments with limited signal strength.

Disadvantages

The observation that slight phase misalignments can significantly affect the output underlines the need for precise phase control when using lock-in amplifiers. This precision in phase alignment is crucial for accurate signal recovery, especially when dealing with weak signals.

The finite bandwidth of the lock-in amplifier is indeed a potential limitation, especially for signals with broad frequency spectra. This restricts the range of frequencies that can be effectively analyzed and may require careful consideration when designing experiments or selecting equipment for a broader range of frequencies.

Its also observed that the mutual inductance EMF is characterized by being 90 degrees out of phase with the current in the primary coil. It is directly proportional to both the current in the primary coil and the frequency of the applied signal. These observations underscore both the strengths and limitations of the lock-in amplifier, making it a valuable tool for experiments involving weak signals and phase-sensitive measurements. However, its effectiveness depends on the frequency range and phase alignment.

VIII. PRECAUTIONS AND SOURCES OF ERROR

1. External electrical noise, thermal noise, or elec tromagnetic interference can affect the input signal, adding unwanted components.
2. The lock-in amplifier relies on phase-sensitive detection, so any misalignment between the ref erence signal and the input signal's phase will cause inaccurate signal extraction
3. The low-pass filter in the lock-in amplifier, used to smooth the output signal, can introduce er rors if not correctly configured. If the filter's time constant is too short, it may pass noise; if too long, it may attenuate the desired signal.
4. Fluctuations in the amplitude of the input sig nal or reference signal can lead to variations in the measured output.
5. The lock-in amplifier has a limited bandwidth, meaning it can only effectively analyze signals within a specific frequency range.
6. If the input signal contains harmonics (multiples of the reference frequency), the lock-in amplifier may detect signals at these harmonic frequen cies.
7. A drift in the reference signal's frequency or phase can desynchronize the phase-locked loop (PLL), which may lead to measurement errors over time.

[1] SPS, *STUDY OF LOCK-IN AMPLIFIER*, NISER (2023).