Experiment: Quality Factor of an Inductor

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Section: 2

Purpose:

The aim of this lab is to use two alternative ways to determine the inductance value and quality factor value of an inductor at a frequency range of 1-5 Mhz. In simulation part, it is learnt how to simulate designed circuit by using LTspice and in hardware part, designs were implemented.

Methodology:

All real inductors appear to have internal resistances due to the winding of a physical wire. On the other hand, LTSpice, comprises only ideal components. As a result, in order to create an actual inductor, ideal inductor must connect in series with a resistance. Two methods have been developed to calculate the internal resistance of the inductor.

Method 1: Node Analysis with Phase Difference

Simulation Part:

The first method was the inductor and the node analysis method was used to calculate its internal resistance. In addition to the inductor and its internal resistance, a 220-ohm resistor was connected in series through the simulation. Then, it was connected in series next to the voltage source inductor, which produces a sine wave with an amplitude of 1V as a power source *(Figure 1)*. Node analysis was performed at Vout1 point and 2 transfer function equation with 2 unknowns was obtained. Two equations were solved by giving 1 Hz, 2 Hz, 3 Hz and 4 Hz respectively. RL1 was found from the equation. Then the peak difference between Vin and Vout was calculated and Phase difference was found. In addition, a code was written on LTspice for phase difference calculation. L was calculated by substituting the found values. Finally, RL1 and L values and Q factors were calculated.

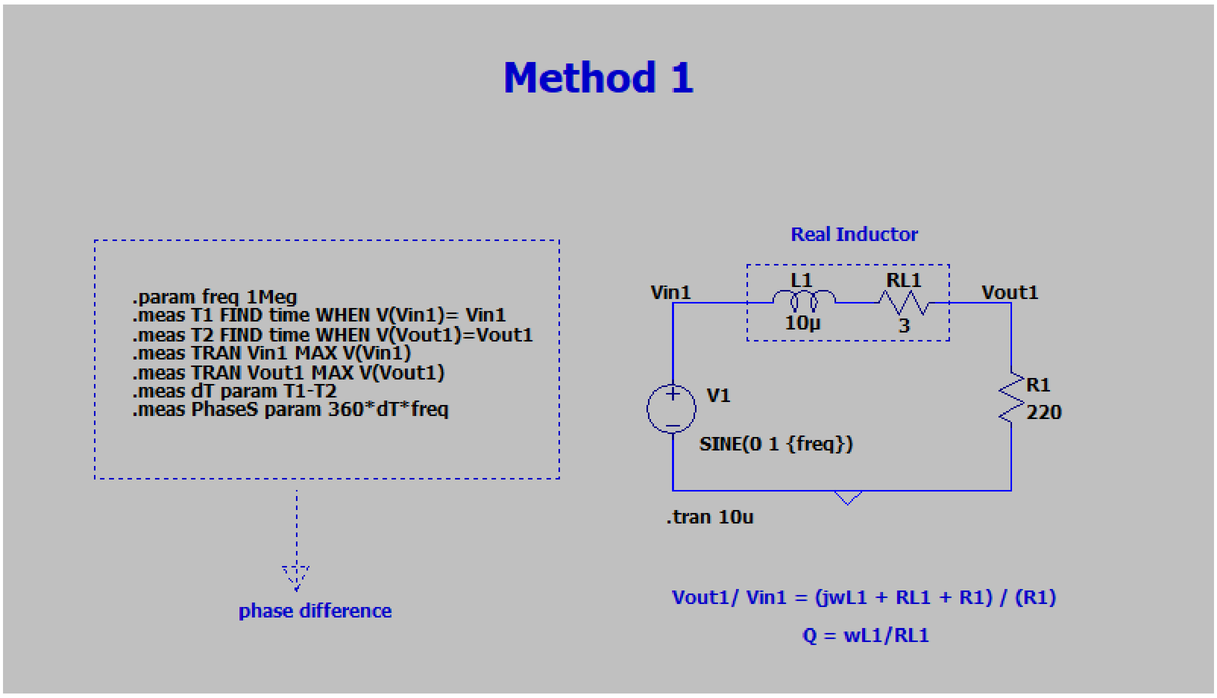


Figure 1

Hardware Part:

In the hardware part, the method 1 was repeated using 2 different inductors. The first inductor was taken ready from the lab (10 μH), and the second one was wound 23 turns on the toroid T38-8 using the formula (1). The A value of the toroid was found by looking at the data sheet, then it was verified whether it was measured correctly using the machine in the lab *(Figure 2).* Then it was placed on the PCB as designed in the simulation *(Figure 3).* Transfer function was calculated by giving 1Hz, 2 Hz, 3 Hz and 4 Hz frequencies respectively from the signal generator, then the Quality factor was calculated using the formula (2) with the inductor and resistance values found.

$$L = A \times (n)^2 \quad (1) \qquad\qquad Q = \frac{\omega\, L}{R} \quad (2)$$

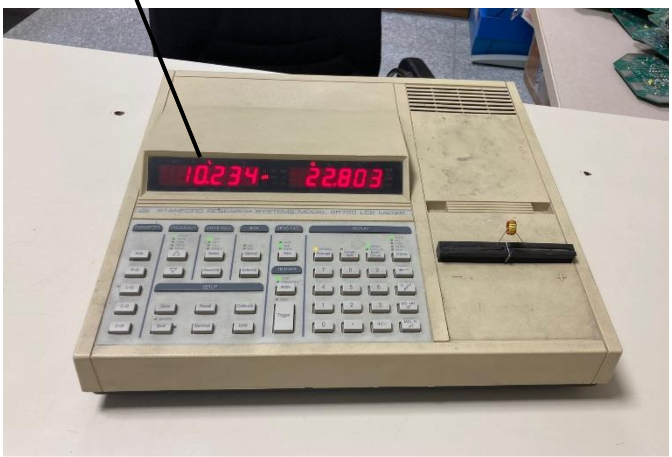


Figure 2

Figure 3

Method 2: Resonating Inductor and Capacitor

Simulation Part:

In the second method; resonance frequencies are used for calculate interior resistance. First, in simulation the ideal capacitor was connected in series with the inductor, and a 220-ohm resistor was connected series next to the capacitor. Then, it was aimed to make a voltage divider by pulling a cable between the resistor and the capacitor. As a power source, a voltage source that produces a sine wave with an amplitude of 0.1 is connected to the circuit. Resonance frequencies were calculated for the inductor and capacitor to eliminate each other. Thus, when the voltage divider was made, it was enough not to know the 220 ohms, Vin and Vout. Vin and Vout were found by looking at the simulation graph and taking their maximum values. Then, the same process was repeated with 4 different capacitors of 1nF, 680pf, 270pF, 120pF. The process can be seen above both in hardware (*Figure 4*) and software (*Figure 5*).

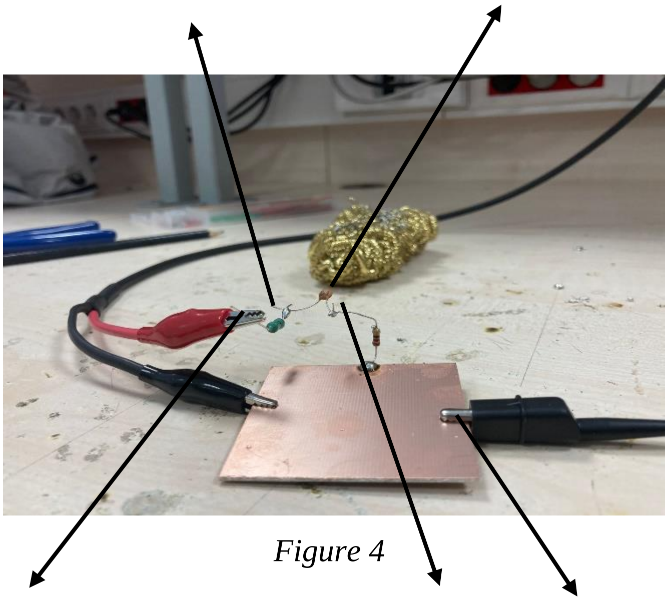


Figure 4

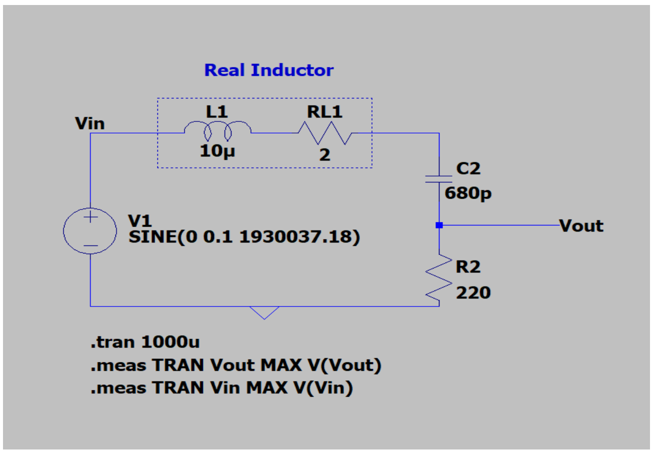


Figure 5

Hardware Part:

The hardware part was repeated with the same inductors used in method 1. Calculated resonance values sequentially were entered into the signal generator. Then, the maximum values of Vin and Vout were measured with the help of an oscilloscope. In addition to the calculated resonance frequencies, the frequency values at which the wavelength is at the top were calculated to find the true value of the inductor. The frequency of capacitor is ignored and the value of capacitance is calculated with multimeter. Then the real value of the inductor was found by equalizing the phase difference of the capacitor and the inductor at the frequency at the maximum point of the Vout.

Results:

The whole methods can be seen as the schematic (*Figure 6*) below:

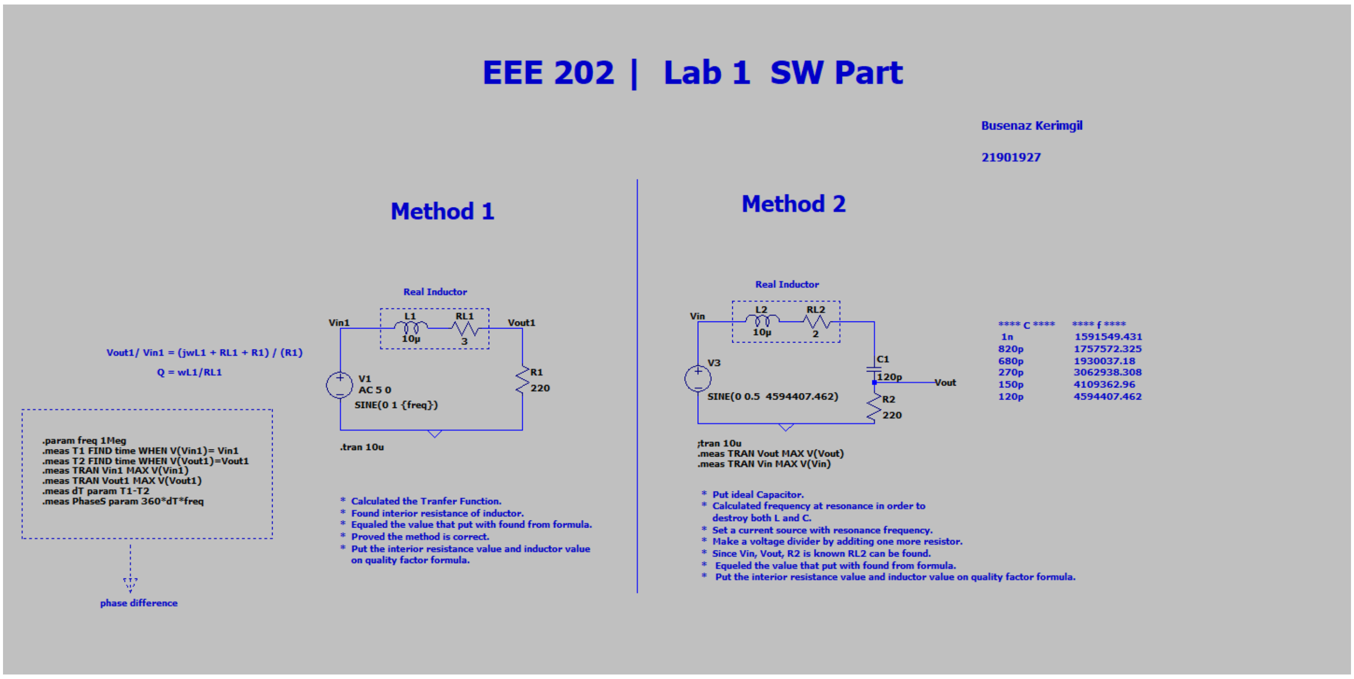


Figure 6

Method 1:

As it can be seen on the *Figure 7* Transfer Function Method is used in order to calculate inductors interior resistance.

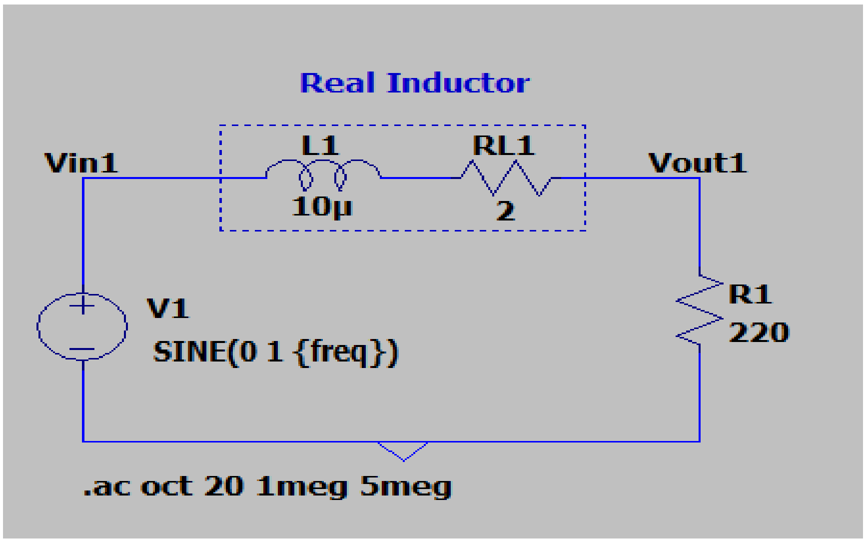


Figure 7

On Vout1 point there is a voltage divider made:

$$Vout1 = Vin1\,\frac{R1}{(jwL1 + RL1 + R1)}$$

Transfer Function: $$\frac{Vout1}{Vin1} = \frac{R1}{jwL1+RL1+R1}$$

Amplitude Equation: $$\frac{|Vin1|}{|Vout1|} = (\frac{(wL1)^2 + (RL1+R1)^2}{R1}$$

$$\sqrt{\frac{\frac{|Vin1|}{|Vout1|} + R1 - (RL1 + R1)^2}{w^2}} = L$$

Phase Equation: $\theta = \Delta t \times 2 \times \pi \times f$

$$\theta = \arctan\left(\frac{wL}{RL1+R1}\right) \tag{3}$$

$$\frac{\tan(\theta)}{w} \times (RL1 + R1) = L \tag{4}$$

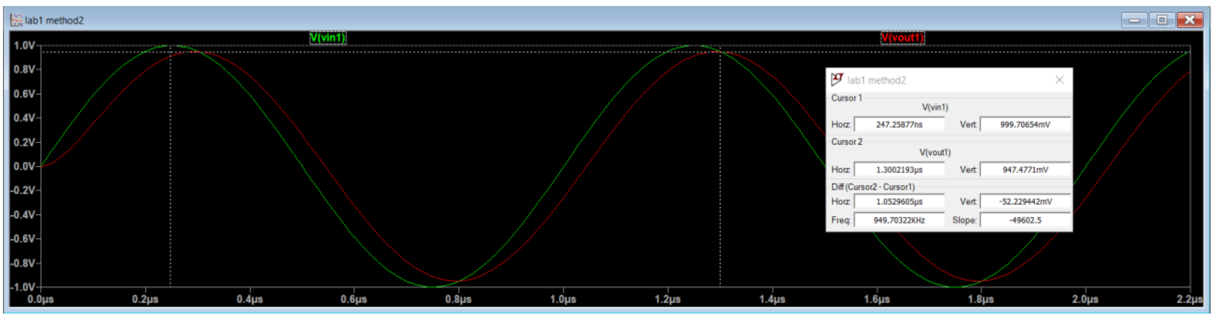
Combining (3) and (4): $$\sqrt{\frac{\frac{|Vin1|}{|Vout1|} + R1 - (RL1+R1)^2}{w^2}} = \frac{\tan(\theta)}{w} \times (RL1 + R1) \tag{5}$$

The results of simulation are below;

Frequency (Hz)	Vin (mV)	Vout (mV)	Delta (ns)	R (Ohm)	Q Factor	L (μH)
1000000	999.996	949.43	43.54	3.0123	21.11999619	10.1254
2000000	1000.0	869.35	42.21	3.4986	17.93823724	9.98836
3000000	999.995	779.879	36.18	3.0168	18.86017785	9.0555
4000000	1060	701.698	30.7	3.9862	17.33889293	11.0002

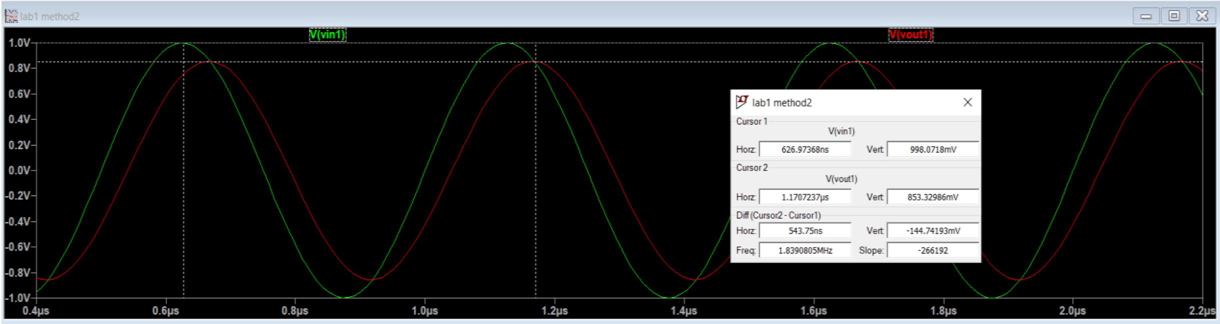
The results of simulation graphs are below;

<u>For 1 MHz:</u>



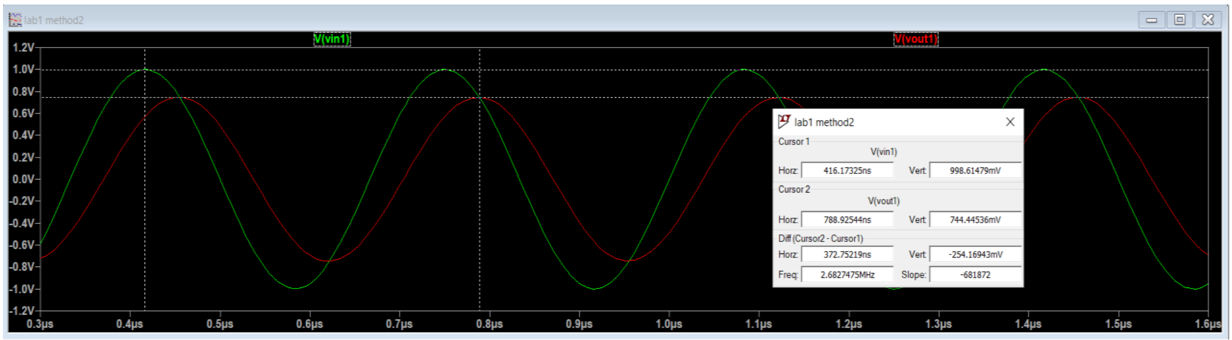

```
vin1: MAX(v(vin1))=0.999996 FROM 0 TO 1e-005
vout1: MAX(v(vout1))=0.949423 FROM 0 TO 1e-005
```

For 2 MHz:



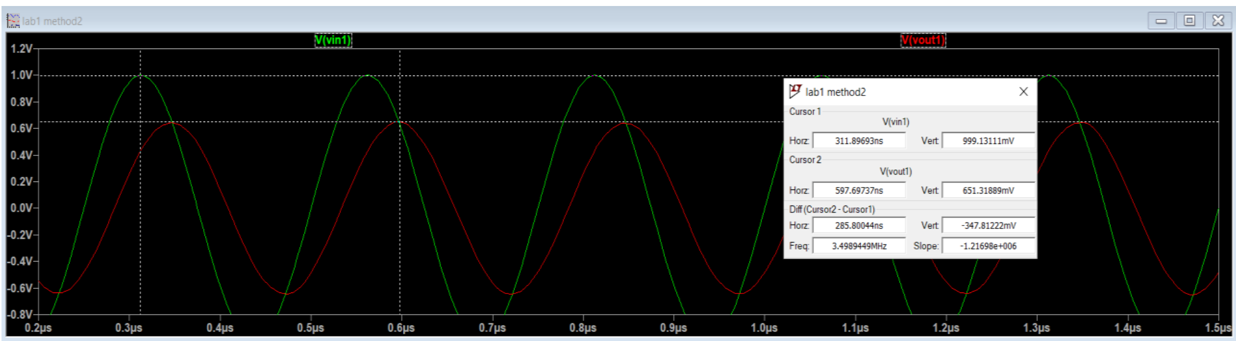

```
vin1: MAX(v(vin1))=1 FROM 0 TO 1e-005
vout1: MAX(v(vout1))=0.869354 FROM 0 TO 1e-005
```

For 3 MHz:




```
vin1: MAX(v(vin1))=0.999995 FROM 0 TO 1e-005
vout1: MAX(v(vout1))=0.779898 FROM 0 TO 1e-005
```

For 4 MHz:




```
vin1: MAX(v(vin1))=0.999994 FROM 0 TO 1e-005
vout1: MAX(v(vout1))=0.701698 FROM 0 TO 1e-005
```

The results of hardware below;

Frequency (Hz)	Vin (mV)	Vout (mV)	Dt (ns)	R (ohm)	Q	L(μH)
1000000	1000	960	48	5.23984729	23.92084594	19.948732
2000000	960	900	56	3.58920892	23.903667	13.6547389
3000000	980	740	56	20.9834242	1.986169954	1.0525005
4000000	960	500	58	3.42491324	18.35362536	10.004412

For axial Inductor 10μH

Frequency (Hz)	Vin (mV)	Vout (mV)	Dt (ns)	R (ohm)	Q	L(μH)
1000000	1000.08	1000.04	56	5.011313455	15.60412563	12.4454653
2000000	1000	960	58	4.098312033	23.49394123	15.3243136
3000000	960	800	62	11.00424233	2.030395111	3.5559925
4000000	940	540	56	9.994234223	5.654575049	8.99434677

For T38-8 Toroid

The results of hardware graphs of 10 μH Inductor are below;

<u>For 1 MHz:</u>

Vin Max = 1.0 V   Vout Max = 960 mV

Phase difference:

Delta = 48.00 ns

<u>For 2 MHz:</u>

Vin Max = 960.0 mV   Vout Max = 900 mV

Phase difference:

Delta = 58.00 ns

<u>For 3 MHz:</u>

Vin Max = 980.0 mV   Vout Max = 740 mV

Phase Difference:

Delta = 56.00 ns

<u>For 4 MHz:</u>

Vin Max = 940.0 mV   Vout Max = 540 mV

Phase Difference:

Delta = 58.00 ns

The results of hardware graphs for T38-8 toroid is below:

<u>For 1 MHz:</u>

Vin Max =1000.08 mV   Vout Max = 1000.04 mV

Phase Difference:

Delta = 56 ns

For 2 MHz:

Vin Max =1000 mV Vout Max = 960.00 mV

Phase Difference**:**

Delta = 58 ns

For 3 MHz:

Vin Max =960 mV Vout Max = 800.00 mV

Phase Difference:

Delta = 62.00 ns

For 4 MHz:

Vin Max =960 mV   Vout Max = 500.00 mV

Phase Difference:

Delta = 56.00 n

Method 2:

As it can be seen on the *Figure 8* Resonance Method is used in order to calculate inductors interior resistance.

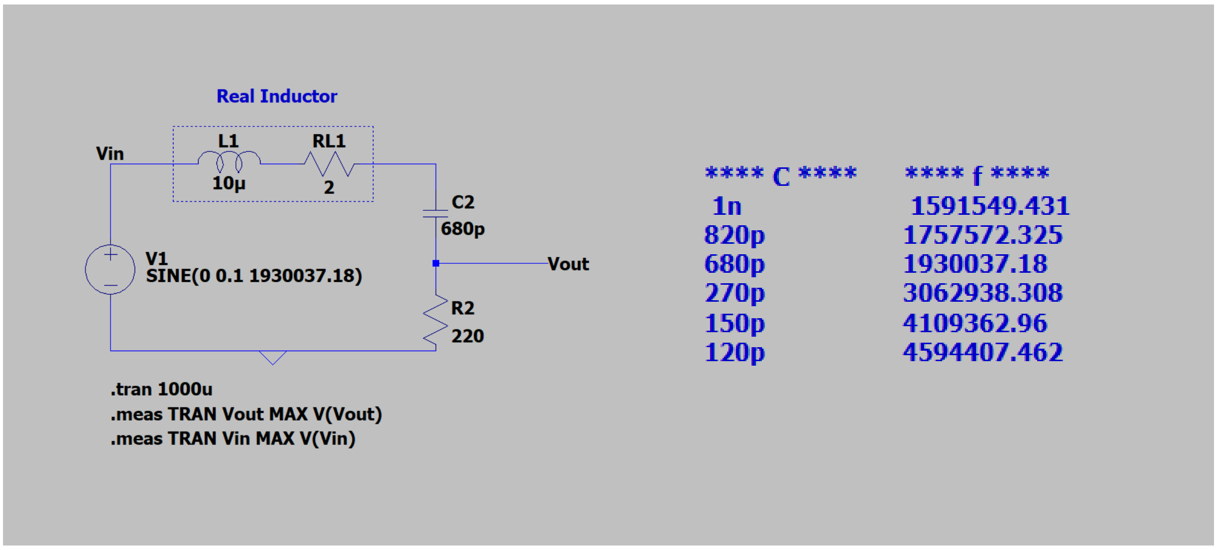


Figure 8

Six capacitors with resonance frequencies ranging from 1 to 5 Hz were chosen. All of their resonance frequencies were calculated using the formula in Equation (5).

$$f = \frac{1}{2\pi\sqrt{L1C2}} \qquad (6)$$

The resonances of the selected 4 capacitors with $10\mu H$ are as follows:

For C1 = 1nF:

$$f = \frac{1}{2\pi\sqrt{10 \times 10^{-6} \times 1 \times 10^{-9}}} = 1591549.431\ Hz \qquad (7)$$

For C1 = 680pF:

$$f = \frac{1}{2\pi\sqrt{10 \times 10^{-6} \times 680 \times 10^{-6}}} = 1930037.18\ Hz \qquad (8)$$

For C1 = 680pF:

$$f = \frac{1}{2\pi\sqrt{10 \times 10^{-6} \times 270 \times 10^{-6}}} = 3062938.308\ \ Hz \qquad (9)$$

For C1 = 680pF:

$$f = \frac{1}{2\pi\sqrt{10 \times 10^{-6} \times 120 \times 10^{-6}}} = 4594407.462\ Hz \qquad (10)$$

Since the resonance frequencies are known the capacitor and the inductor eliminates each other and only resistors RL1 and R2 left. Vout can be calculated by Voltage Divider method. (Equation 10)

$$Vout = Vin \times \frac{R2}{R2 + RL1} \qquad (11)$$

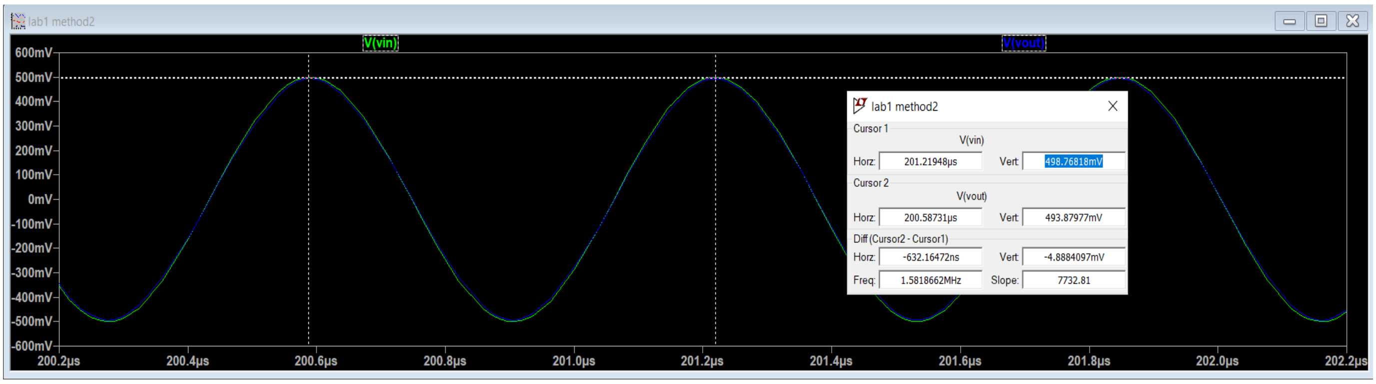
The results of the simulation are below;

Capacitance	Frequency	Internal Resistor	Q factor	Inductor (Calculated)
1nF	1591549.431 Hz	2.67 Ω	37.45	9.32 μH
680pF	1930037.18 Hz	2.22 Ω	54.62	8.75 μH
270pF	3062938.308 Hz	3.58 Ω	53.75	7.65 μH
120pF	4594407.462 Hz	3.34 Ω	86.47	10.39 μH

For axial inductor 10μH

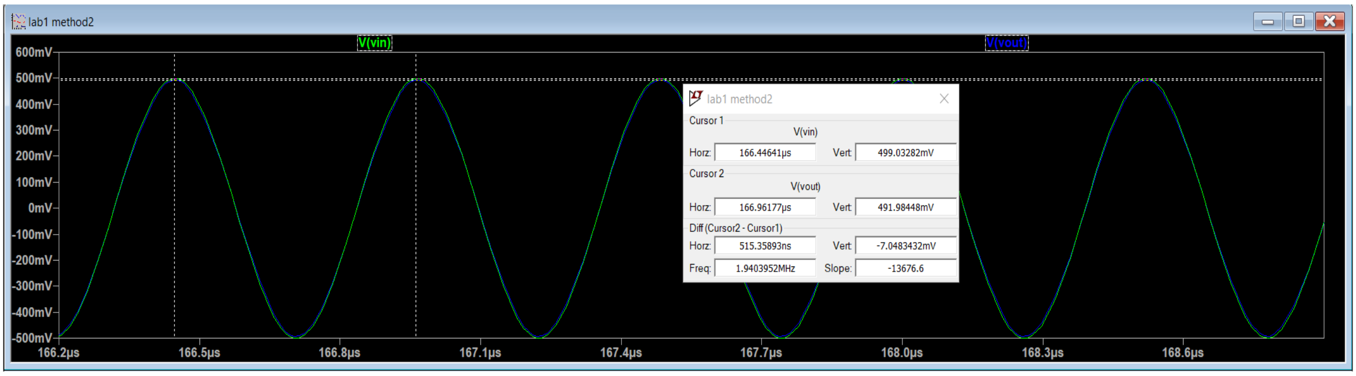
The results of simulation graphs are below;

<u>For 1nF:</u>



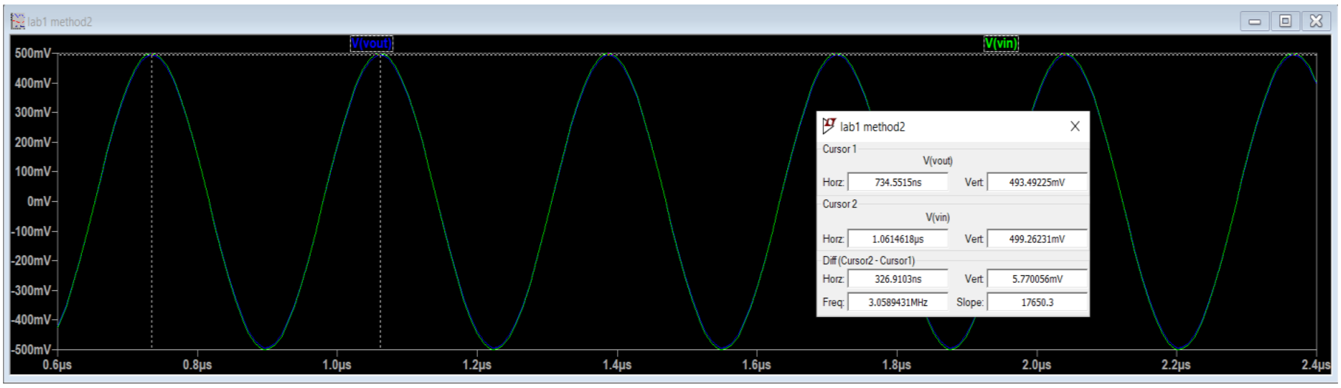

```
vout: MAX(v(vout))=0.494601 FROM 0 TO 0.001
vin: MAX(v(vin))=0.5 FROM 0 TO 0.001
```

For 680pF:



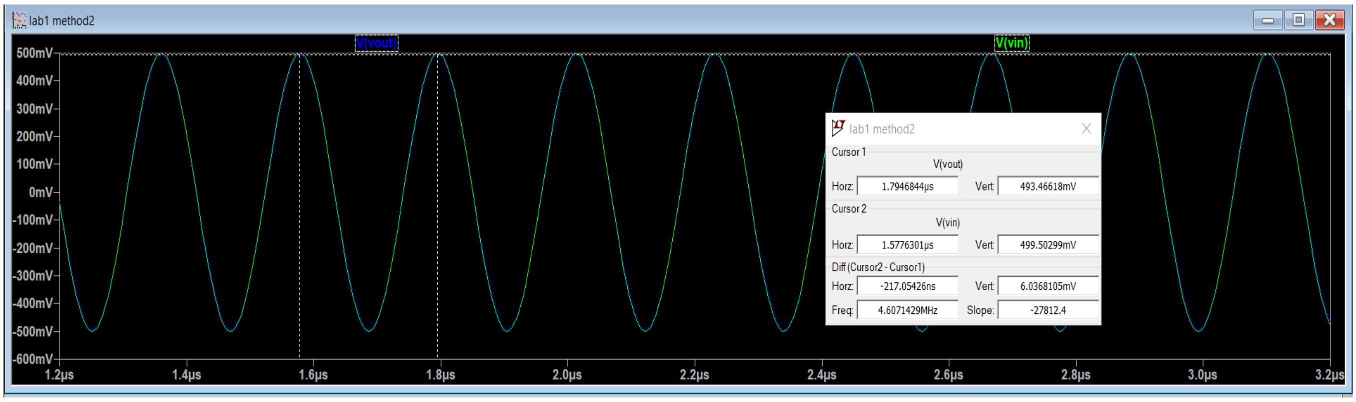
vout: MAX(v(vout))=0.494605 FROM 0 TO 0.001
vin: MAX(v(vin))=0.499999 FROM 0 TO 0.001

For 270pF:



vout: MAX(v(vout))=0.493998 FROM 0 TO 1e-005
vin: MAX(v(vin))=0.49976 FROM 0 TO 1e-005

For 120pF:



vout: MAX(v(vout))=0.493498 FROM 0 TO 1e-005
vin: MAX(v(vin))=0.499882 FROM 0 TO 1e-005

The results of hardware below;

Capacitance	Frequency	Internal Resistor	Q factor	Inductor (Calculated)
1nF	1591549.431 Hz	3.19 Ω	31.36	11.16 μH
680pF	1930037.18 Hz	2.93 Ω	41.34	10.32 μH
270pF	3062938.308 Hz	6.47 Ω	29.74	7.54 μH
120pF	4594407.462 Hz	3.05 Ω	94.47	8.95 μH

For axial inductor 10μH

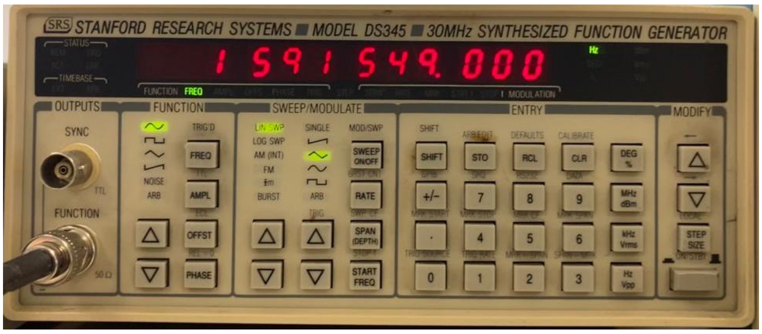
Capacitance	Frequency	Internal Resistance	Q Factor	Inductor (Calculated)
1nF	1591549.431 Hz	13.5 Ω	10.2	11.16 μH
680pF	1930037.18 Hz	4.23 Ω	29.32	10.32 μH
270pF	3062938.308 Hz	8.8 Ω	22.37	7.54 μH
120pF	4594407.462 Hz	3.05 Ω	96.82	8.95 μH

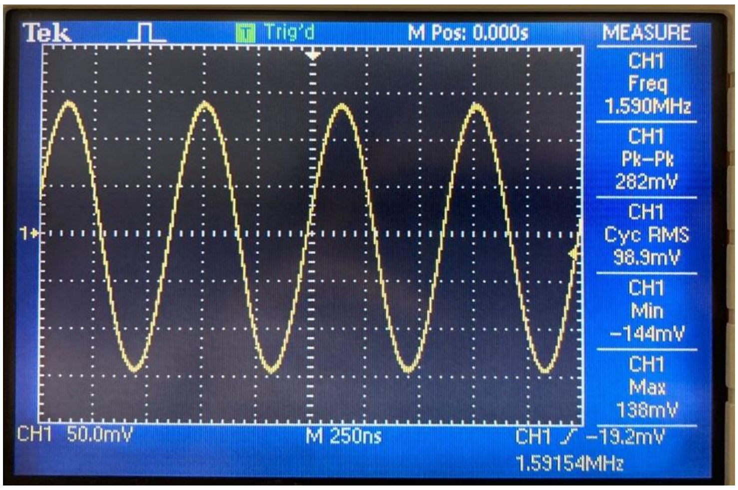
For toroid

The results of hardware graphs for 10μH axial inductor is below:

<u>For 1nF:</u>

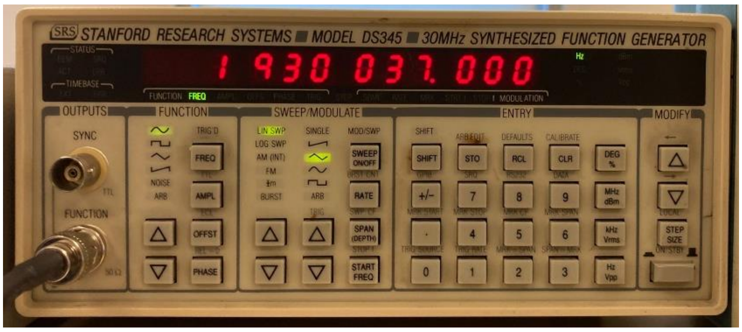
Resonance Frequency: 15549.000 Hz

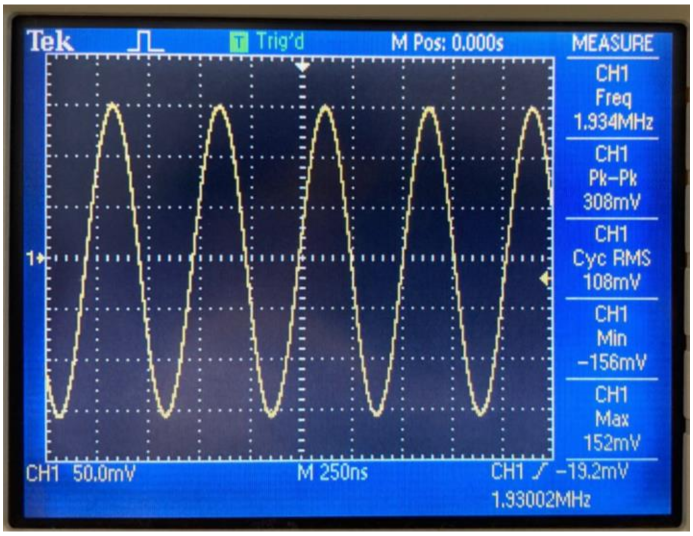




For 680pF:

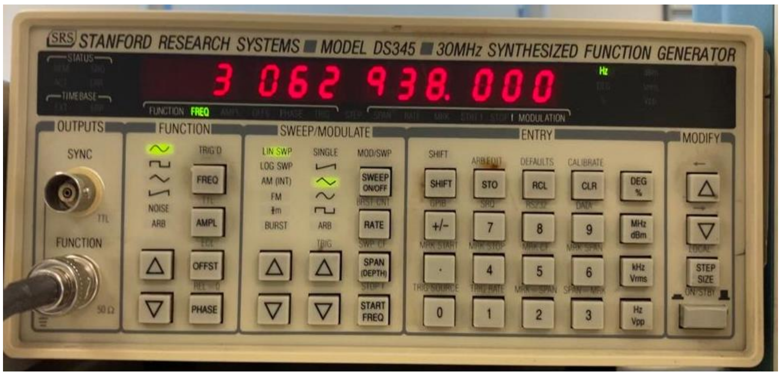
Resonance Frequency: 1930037.000 Hz

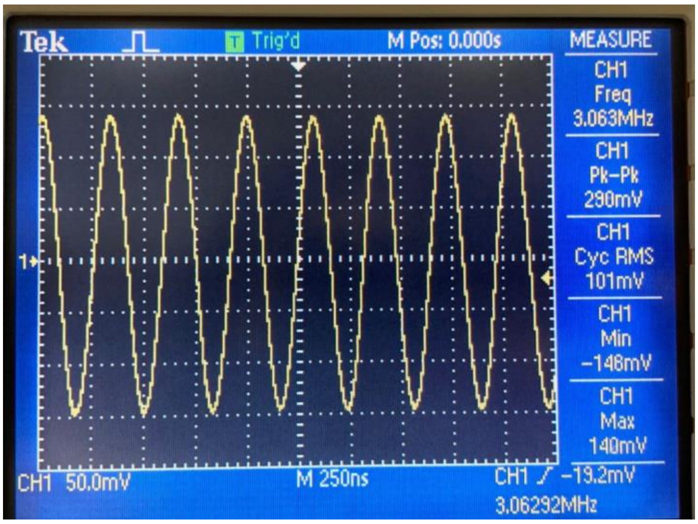




For 270 pF:

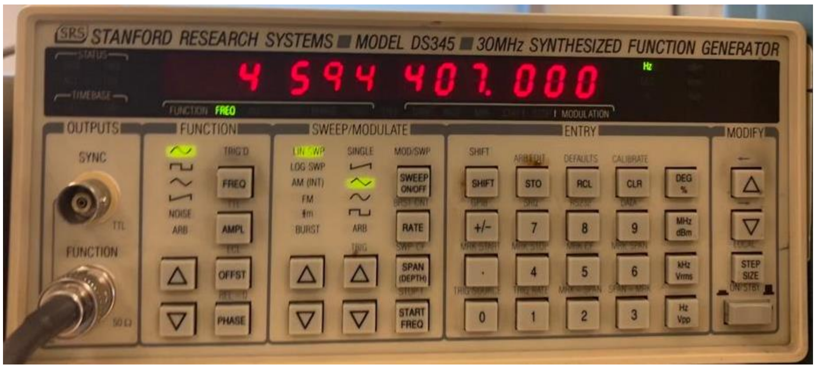
Resonance Frequency: 3062938.000 Hz

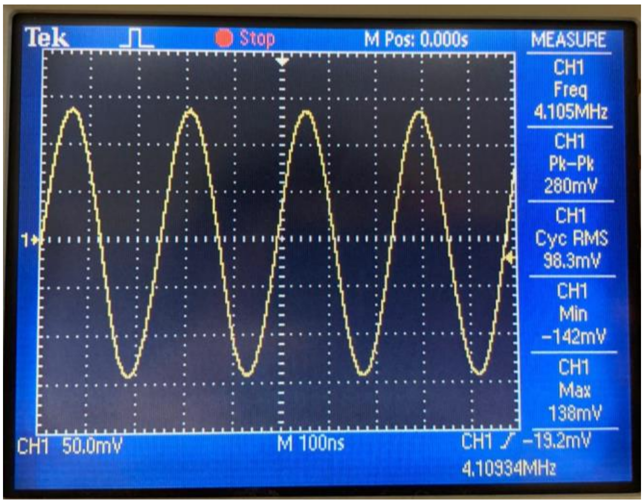




For 120pF:

Resonance Frequency: 4594407.000 Hz

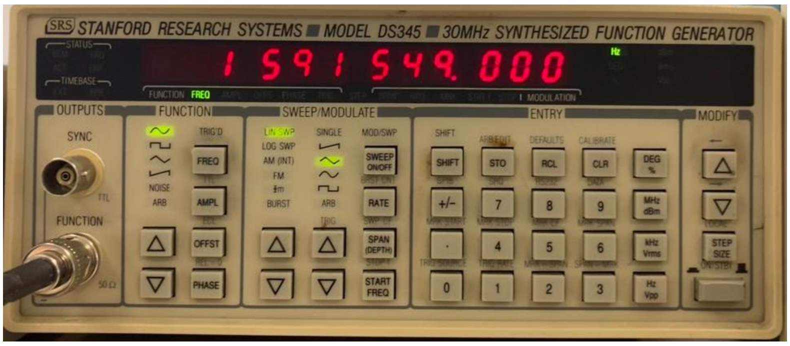


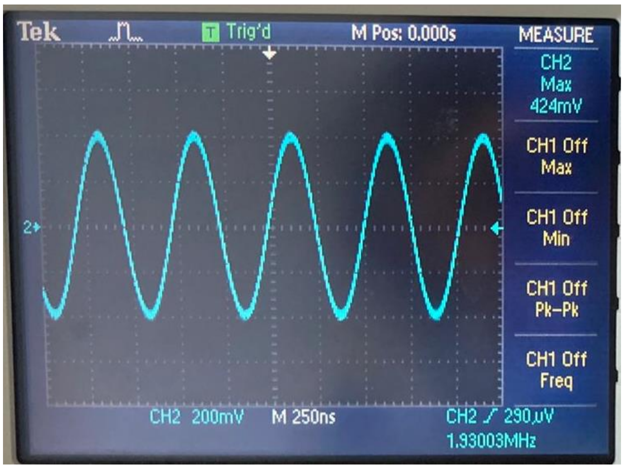


The results of hardware graphs for T38-8 toroid is below:

For 1nF:

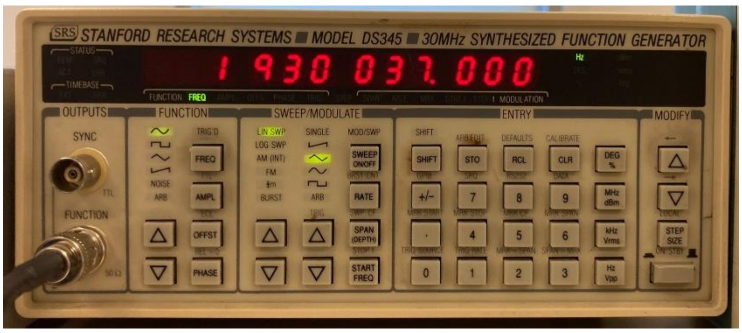
Resonance Frequency: 15549.000 Hz

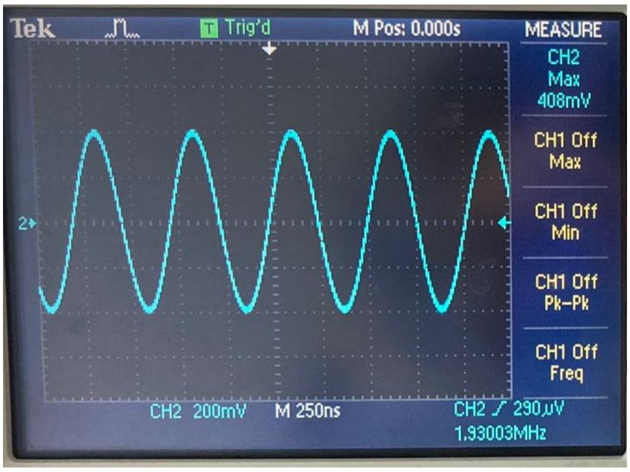




For 680pF:

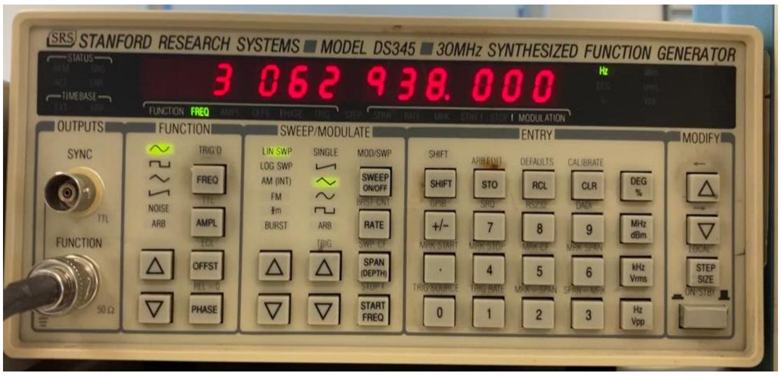
Resonance Frequency: 1930037.000 Hz

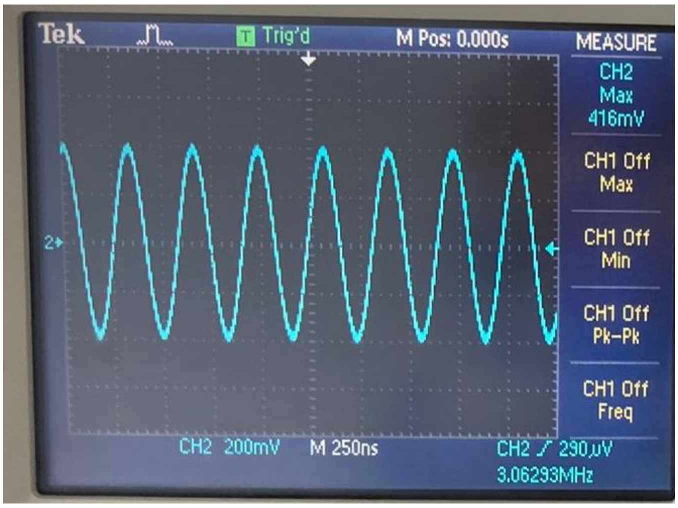




For 270 pF:

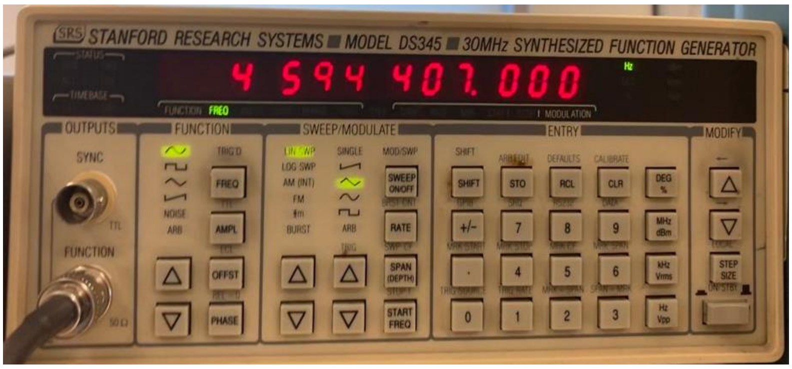
Resonance Frequency: 3062938.000 Hz

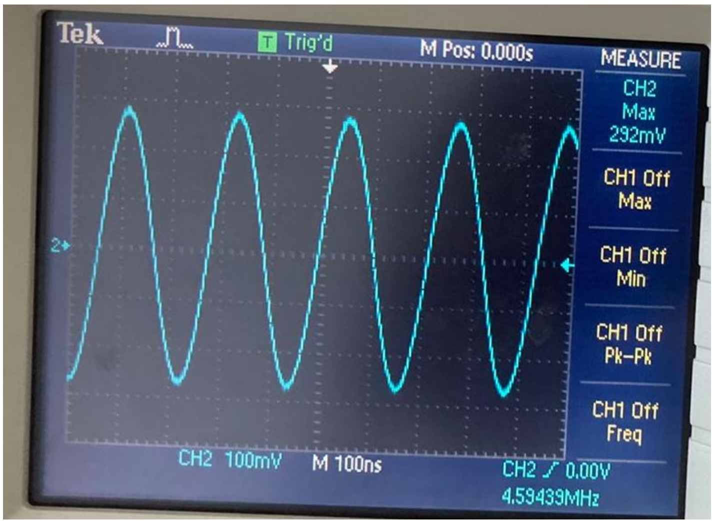




120pF:

Resonance Frequency: 3062938.000 Hz





Conclusion:

The goal of this experiment is to present two different ways for measuring an inductor's quality factor at four different frequencies between the range 1-5 MHz This lab taught me how to create simple circuits to measure the values needed to determine the Q factor and how to use the LTSpice software with its shortcuts. Method 2 was more manageable when compared to method 1 due to method 1 contains two unknowns and two nonlinear equations which made difficult to solve them. When software and hardware applications are compared, it is noticed that the results obtained in hardware do not quite match with the simulation results. When I first made the hardware application, I tried it on the breadboard, but since the breadboard creates its own capacitance at the connection points, I realized that there is quite a difference between the simulation data and the data I measured. Then I repeated the same operations on PCB and got more accurate results. The q factor values I obtained in the 1st method hardware varied between a minimum of 6% and a maximum of 9.876%, according to the software. Since we accepted the capacitor as ideal while performing the software implementation of the 2nd method, the q factor values deviated more than the 1st method, since the real capacitors was used in the hardware application. Also, the resonance values calculated in the software lab were 2.08% when the Vin and Vout were brought back to the same phase ratio in the hardware lab and observed on the oscilloscope. This led to a difference in value between the measured inductor and the inserted inductor. When we examine in general, although more complications occur with the 2nd method, it is reliable and gives accurate data compared to the 1st method, and fewer errors are encountered.