XI'AN JIAOTONG-LIVERPOOL UNIVERSITY

西交利物浦大学

COURSEWORK SUBMISSION COVER Page

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Part A:

➔ **Q1:**

(a) :

There are three main methods to design a high-pass filter using R, L, C, Vs.

✧ **Case 1: Series RC Circuit**

We first choose the resistor's voltage as the output voltage terminal, then apply frequency $f = 0$ and $f = \infty$ to verify our design, and finally build our circuit schematic in LTspice as below.

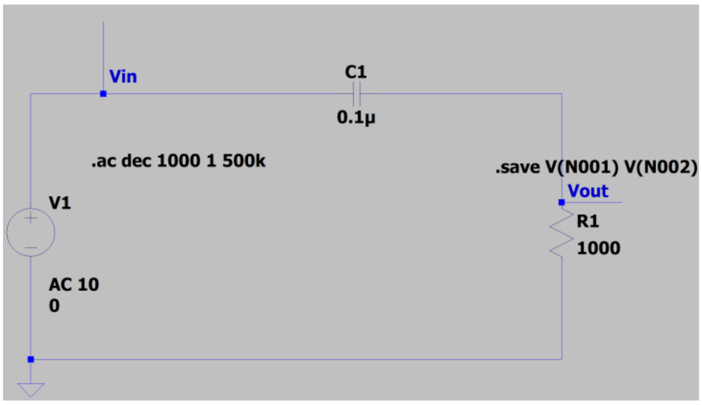

Figure 1: RC high-pass filter circuit

To determine the frequency response, we have to find the transfer function of this circuit. Then, apply KVL in frequency domain:

$$Vout(j\omega) = Vs(j\omega) * \frac{R}{R+1/j\omega C} \tag{1}$$

Thus, the frequency response of this circuit is:

$$H(j\omega) = \frac{Vout(j\omega)}{Vs(j\omega)} = \frac{1}{1+1/j\omega RC} \tag{2}$$

✧ **Case 2: Series RL Circuit**

We first choose the inductor's voltage as the output voltage terminal, then apply frequency $f = 0$ and $f = \infty$ to verify our design, and finally build our circuit schematic in LTspice as below.

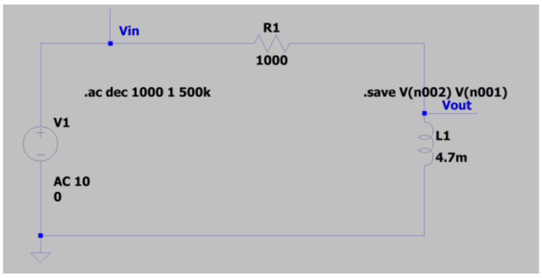

Figure 2: RL high-pass filter circuit

To determine the frequency response, we have to find the transfer function of this circuit. Then, apply KVL in frequency domain:

$$Vout(j\omega) = Vs(j\omega) * \frac{j\omega L}{R+j\omega L} \tag{3}$$

Thus, the frequency response of this circuit is:

$$H(j\omega) = \frac{Vout(j\omega)}{Vs(j\omega)} = \frac{1}{1-jR/\omega L} \tag{4}$$

✧ Case 3: Series RLC Circuit

We first choose the inductor's voltage as the output voltage terminal, then apply frequency $f = 0$ and $f = \infty$ to verify our design, and finally plot the Bode plot and our circuit schematic in LTspice as below.

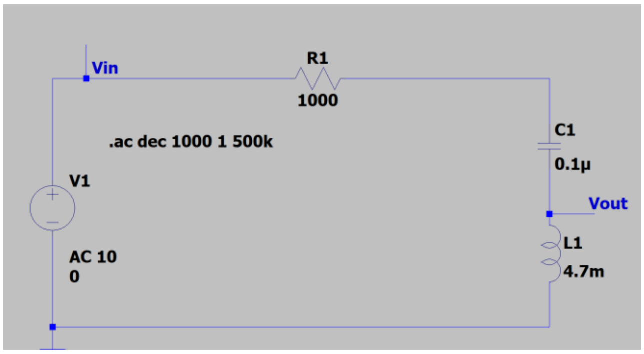

Figure 3: RLC high-pass filter circuit

To determine the frequency response, we have to find the transfer function of this circuit. Then, apply KVL in frequency domain:

$$Vout(j\omega) = Vs(j\omega) * \frac{j\omega L}{1/j\omega C+R+j\omega L} \tag{5}$$

Thus, the frequency response of this circuit is:

$$H(j\omega) = \frac{Vout(j\omega)}{Vs(j\omega)} = \frac{j\omega L}{1/j\omega C+R+j\omega L} \tag{6}$$

(b):

By simulating these three circuits in LTspice, we can also determine the corresponding Bode Plots.

✧ Case 1: Series RC circuit

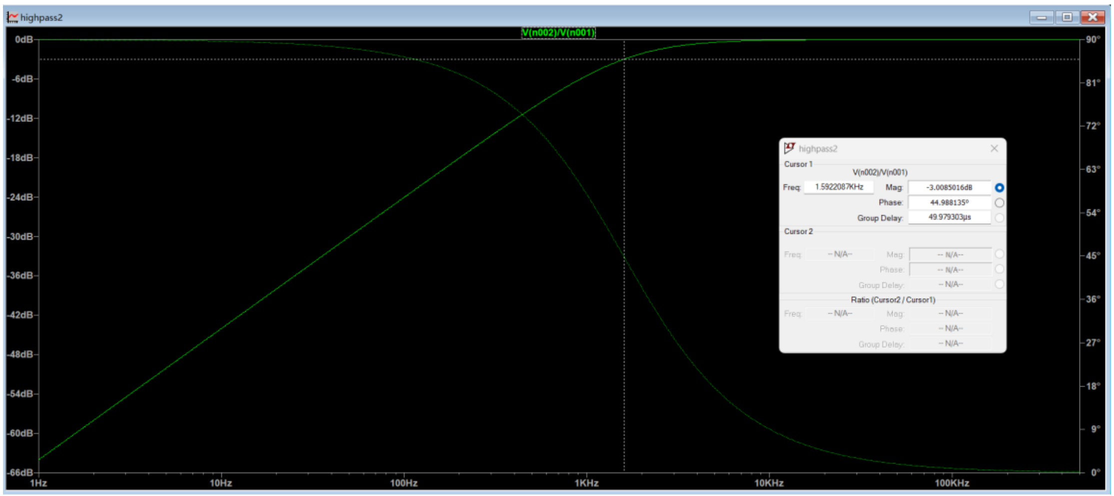

Figure 4: RC high-pass filter Bode plot

✧ Case 2: Series RL circuit

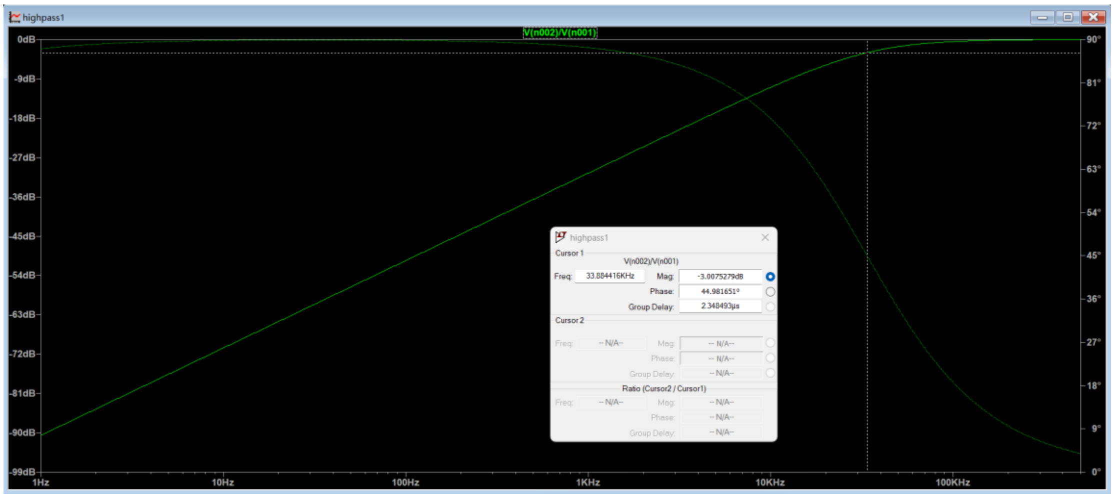

Figure 5: RL high-pass filter Bode plot

✧ Case 3: Series RLC circuit

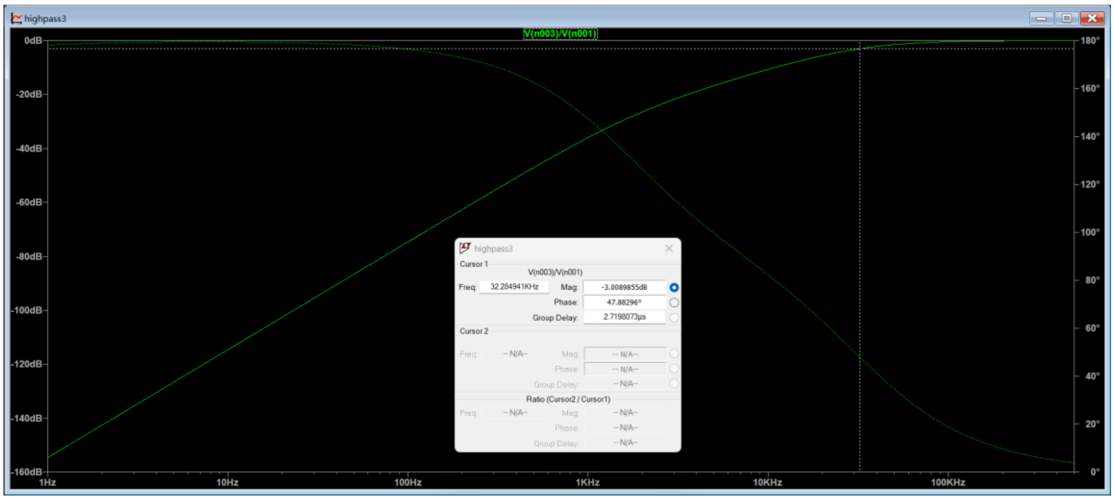

Figure 6: RLC high-pass filter Bode plot

(c):

There are three main methods to design a low-pass filter using R, L, C, Vs.

✧ **Case 1: Series RC Circuit**

We first choose the capacitor's voltage as the output voltage terminal, then apply frequency $f = 0$ and $f = \infty$ to verify our design, and finally plot the Bode plot and our circuit schematic in LTspice as below.

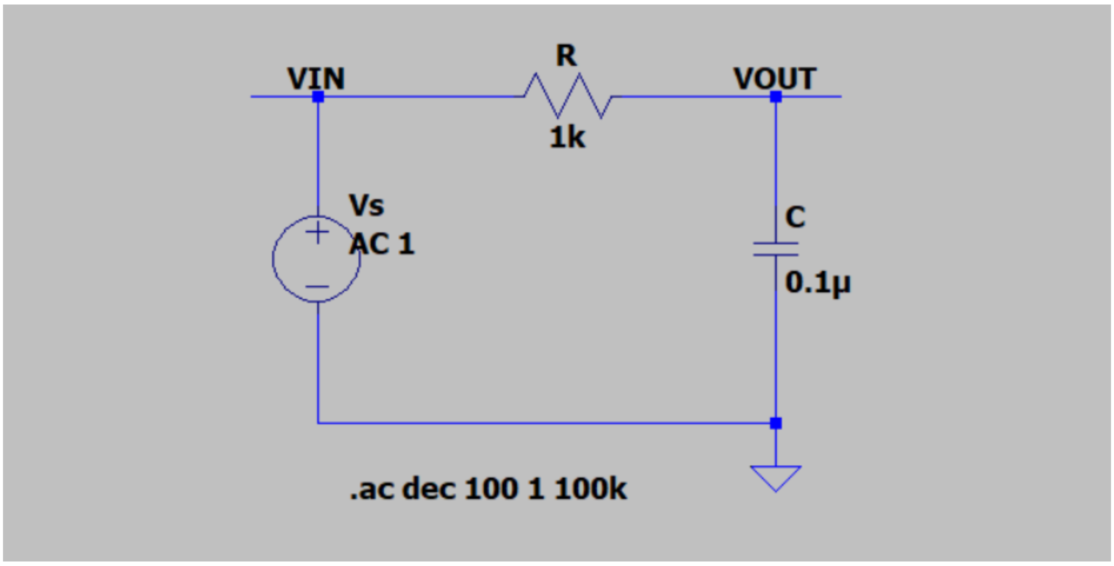

Figure 7: RC low-pass filter circuit

To determine the frequency response, we have to find the transfer function of this circuit.

Then, apply KVL in frequency domain:

$$Vout(j\omega) = Vs(j\omega) * \frac{1/j\omega C}{R+1/j\omega C} \tag{1}$$

Thus, the frequency response of this circuit is:

$$H(j\omega) = \frac{Vout(j\omega)}{Vs(j\omega)} = \frac{1/RC}{j\omega+1/RC} \tag{2}$$

✧ Case 2: Series RL circuit

We first choose the resistor's voltage as the output voltage terminal, then apply frequency $f = 0$ and $f = \infty$ to verify our design, and finally plot the Bode plot and our circuit schematic in LTspice as below.

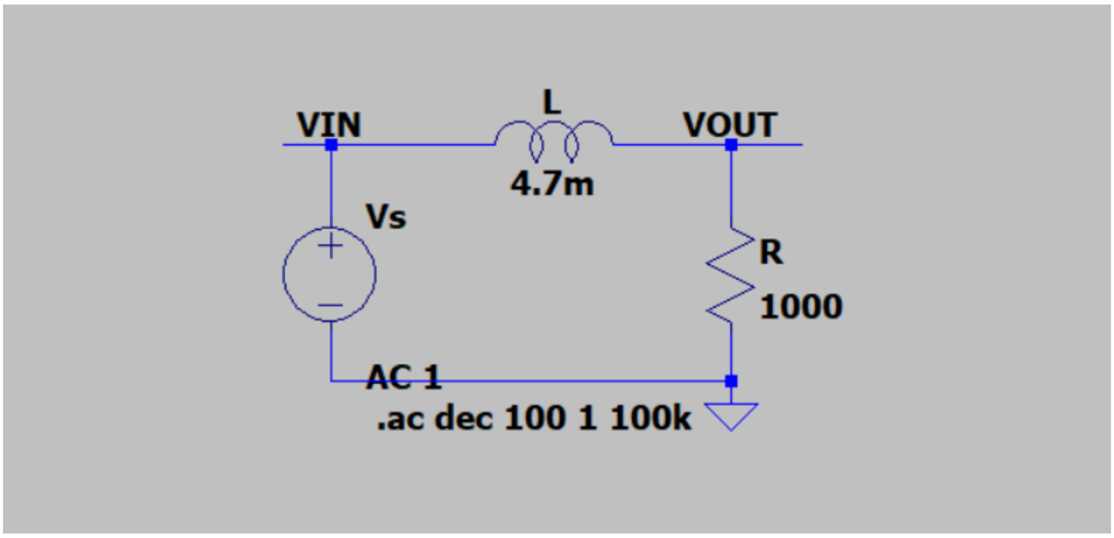

Figure 8: RL low-pass filter circuit

To determine the frequency response, we have to find the transfer function of this circuit. Then, apply KVL in frequency domain:

$$Vout(j\omega) = Vs(j\omega) * \frac{R}{R+j\omega L} \tag{3}$$

Thus, the frequency response of this circuit is:

$$H(j\omega) = \frac{Vout(j\omega)}{Vs(j\omega)} = \frac{R/L}{j\omega+R/L} \tag{4}$$

✧ Case 3: Series RLC circuit

We first choose the capacitor's voltage as the output voltage terminal, then apply frequency $f = 0$ and $f = \infty$ to verify our design, and finally plot the Bode plot and our circuit schematic in LTspice as below.

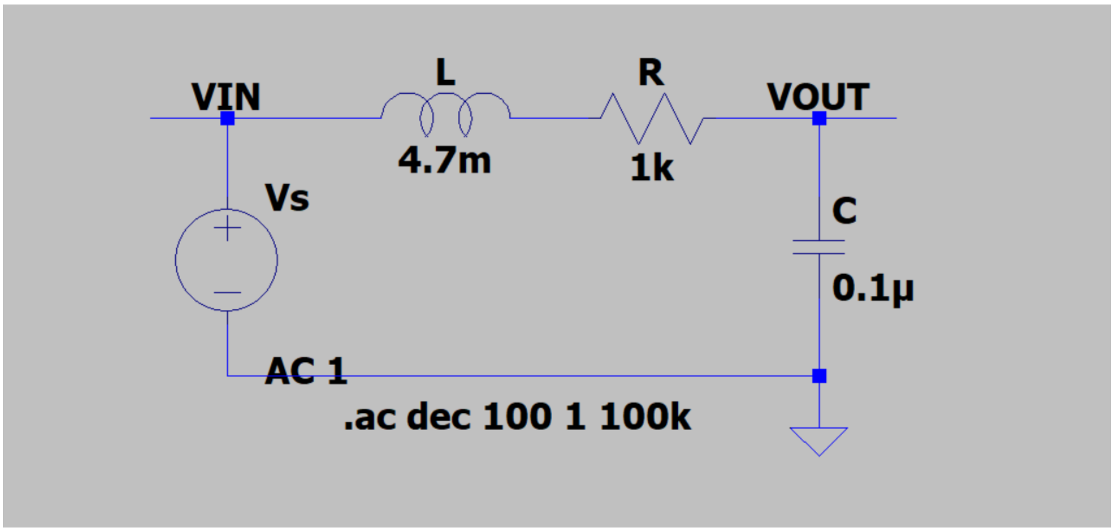

Figure 9: RLC low-pass filter circuit

To determine the frequency response, we have to find the transfer function of this circuit. Then, apply KVL in frequency domain:

$$Vout(j\omega) = Vs(j\omega) * \frac{1/j\omega C}{1/j\omega C + R + j\omega L} \tag{5}$$

Thus, the frequency response of this circuit is:

$$H(j\omega) = \frac{Vout(j\omega)}{Vs(j\omega)} = \frac{1/RC}{j\omega + \frac{[1-(\omega)^2 LC]}{RC}} \tag{6}$$

(d):

By simulating these three circuits in LTspice, we can also determine the corresponding Bode Plots.

✧ **Case 1: Series RC circuit**

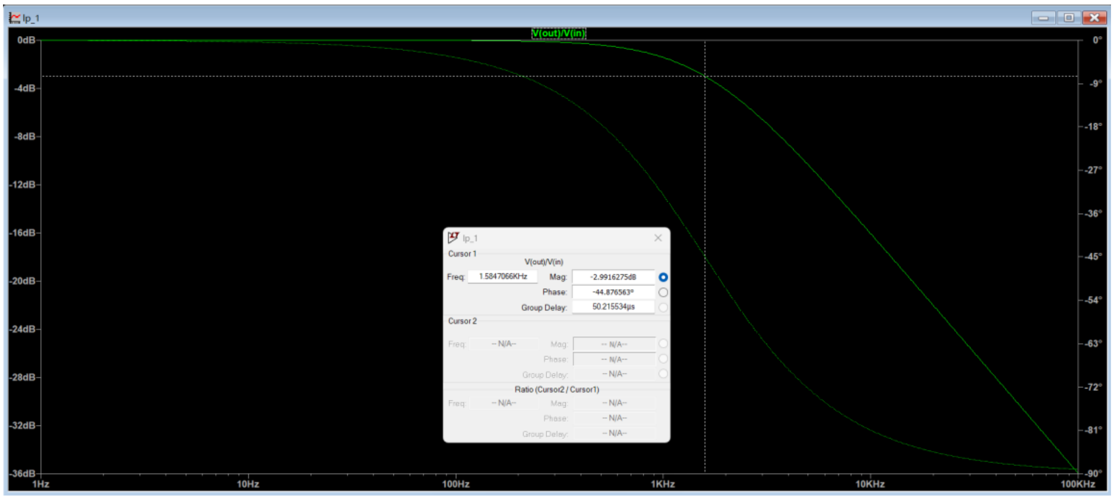

Figure 10: RC low-pass filter Bode plot

✧ Case 2: Series RL circuit

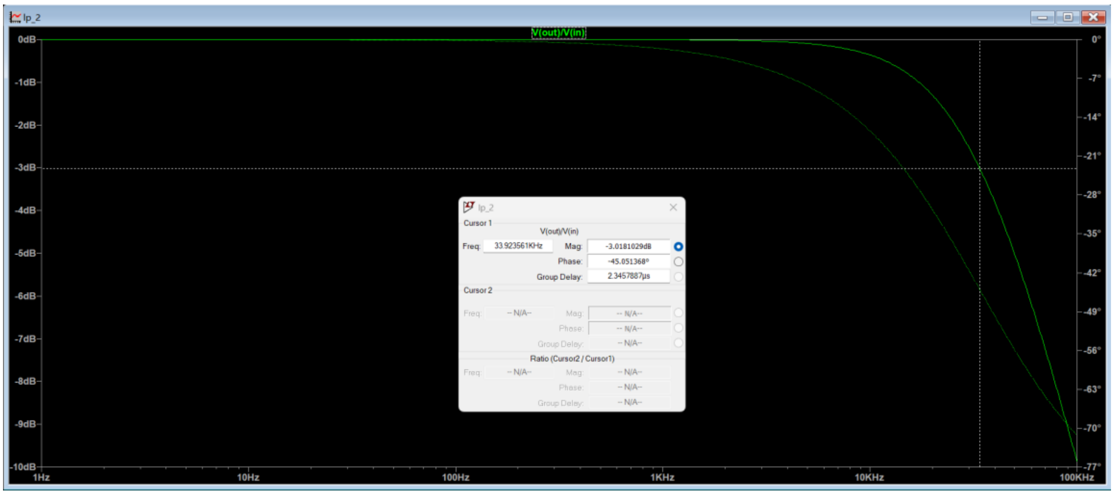

Figure 11: RL low-pass filter Bode plot

✧ Case 3: Series RLC circuit

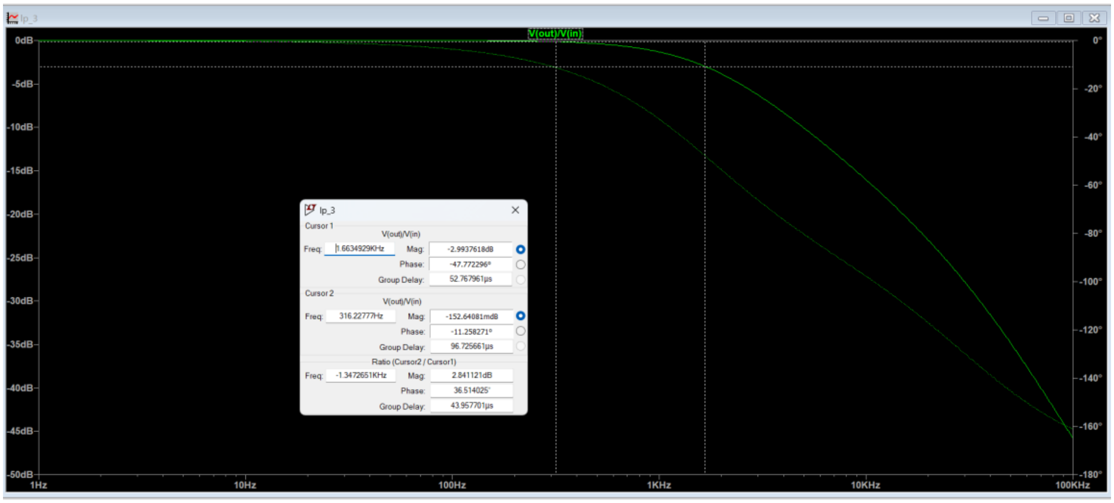

Figure 12: RLC low-pass filter Bode plot

- **Part B:**

1) Action 1:

For the purpose of understanding the behaviors of passive components, we build a Series RC circuit on the ELVIS III breadboard, powered by the function generator (DG1022). Then we gradually vary the frequency from 20 Hz to 20kHz and observe the results by applying digital multimeter (DMM). The measured data is shown in Table 1 with -3 dB frequency ω_c highlighted in yellow. ***Note that V1 and Vin parameters in the table stand for their Root Mean Square (RMS) values.***

Frequency (Hz)	V1(V)	Vin(V)	V1/Vin	20log10(V1/Vin) (dB)
20	0.0473	3.532	0.013392	-37.4632
200	0.460	3.544	0.129797	-17.7347
400	0.898	3.527	0.254607	-11.8826
800	1.600	3.470	0.461095	-6.72419
1500	2.318	3.354	0.691115	-3.20899
1550	2.363	3.375	0.700148	-3.0962
1575	2.442	3.452	0.707416	-3.0065
1600	2.370	3.326	0.712568	-2.94348
1625	2.360	3.356	0.703218	-3.0582

1650	2.369	3.280	0.722256	-2.82618
1675	2.400	3.300	0.727273	-2.76605
1700	2.370	3.230	0.733746	-2.68908
1725	2.420	3.291	0.735562	-2.66761
1750	2.330	3.160	0.737342	-2.64662
1775	2.450	3.272	0.749235	-2.50763
1800	2.400	3.190	0.752351	-2.47159
2000	2.550	3.24	0.787037	-2.0801
2200	2.610	3.233	0.80805	-1.85124
2400	2.690	3.220	0.840625	-1.50795
3000	2.820	3.220	0.875776	-1.15214
4000	2.910	3.120	0.932692	-0.60523
8000	3.090	3.16	0.977848	-0.19457
12000	3.290	3.32	0.990964	-0.07884
14000	3.297	3.324	0.991877	-0.07084
16000	3.300	3.32	0.993976	-0.05248
18000	3.307	3.324	0.994886	-0.04454
20000	3.309	3.322	0.996087	-0.03406

Table 1. Measured data of the series RC Circuit

2) Action 2:

The data has been imported into MATLAB to get the corresponding Bode Plot with frequency in logarithm scale, as shown in Figure 13.

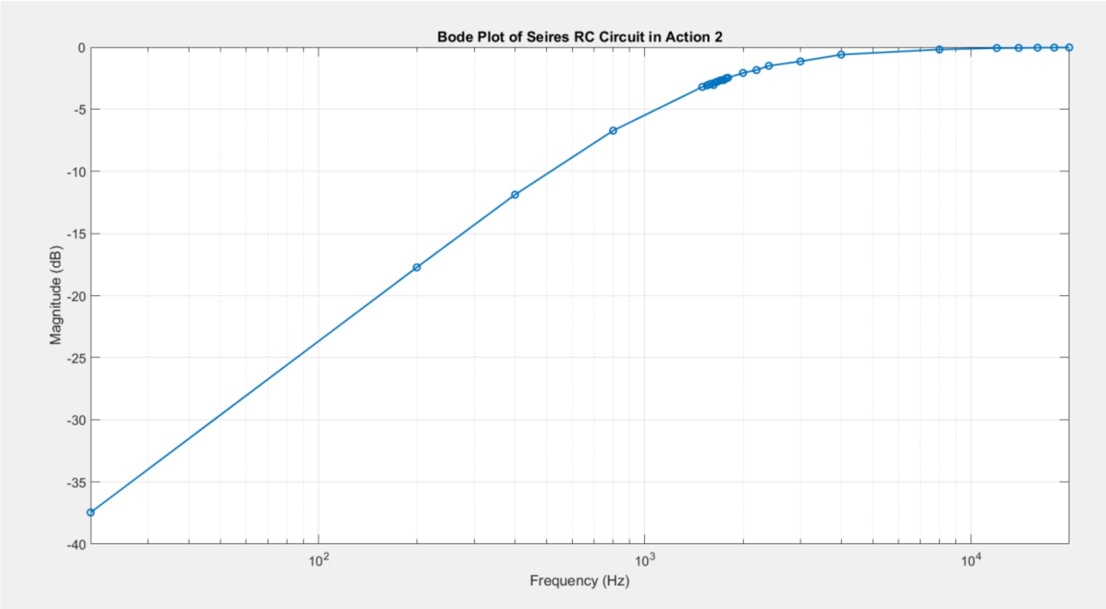

Figure 13: Magnitude Bode plot of the RC circuit

3) Action 3:

Apply KVL to the circuit in Step 1,

$$V_{in} = V_1 + \frac{1}{j\omega C} \times \frac{V1}{R} \tag{1}$$

We can get the frequency response:

$$H(j\omega) = \frac{V_1}{V_{in}} = \frac{j\omega RC}{1+j\omega RC} = \frac{j}{\frac{1}{\omega RC}+j} \tag{2}$$

Therefore, the magnitude of the frequency response is:

$$|H(j\omega)| = \frac{1}{\sqrt{(\frac{1}{\omega RC})^2+1}} \tag{3}$$

At the -3dB point,

$$|H(j\omega_c)| = \frac{1}{\sqrt{2}} \times |H(j\omega)|_{max} = \frac{1}{\sqrt{2}} \tag{4}$$

By neglecting the negative solution, we obtain:

$$\frac{1}{\omega_c RC} = 1 \tag{5}$$

That is:

$$C = \frac{1}{2\pi f_c R} \tag{6}$$

Using our measurements and substituting the value of R and fc into the equation, the result is:

$$C = 0.102\mu F \tag{7}$$

The result measured directly by DMM is about $0.103\mu F$, which aligns with our calculations.

4) Action 4:

In this action, we are required to build a Parallel RLC circuit on the ELVIS III breadboard. The difference between Action 4 and Action 1 lies in the frequency. The parallel RLC circuit features two corner frequencies and one resonant frequency. The measured data is presented in Table 2, highlighting two -3 dB frequencies (ω_{c1}, ω_{c2}) and resonant frequency ω_0 in yellow and blue respectively. ***Note that V1 and Vin parameters in the table stand for their Root Mean Square (RMS) values.***

Frequency (Hz)	V1 (V)	V1/Vin (V)	20log10(V1/Vin) (dB)
20	3.26	0.987879	-0.105926796
500	3.21	0.978659	-0.187376226
2000	3.25	0.981873	-0.158892656
4000	3.15	0.954545	-0.404067722
5000	2.98	0.89759	-0.938436393
6000	2.4	0.710059	-2.974109171
6015	2.398	0.70117	-3.083538546
6025	2.386	0.697253	-3.132191317
6050	2.35	0.687135	-3.259164876
6200	2.15	0.628655	-4.031752923
6300	2.01	0.584302	-4.667247703
6400	1.84	0.533333	-5.460025441
6500	1.66	0.482558	-6.329007091
6550	1.57	0.455072	-6.838388853
6575	1.52	0.44186	-7.094297093

6590	1.49	0.438235	-7.165852973
6800	1.15	0.347432	-9.182603068
7000	1.14	0.32948	-9.643424949
7100	1.18	0.34104	-9.34388183
7200	1.29	0.373913	-8.544587695
7300	1.39	0.408824	-7.769282336
7325	1.45	0.421512	-7.503808807
7350	1.48	0.431487	-7.300648093
7375	1.52	0.443149	-7.069010642
7500	1.70	0.497076	-6.071543694
7700	1.97	0.579412	-4.740253818
7900	2.19	0.647929	-3.769451709
8000	2.29	0.675516	-3.407284317
8050	2.26	0.695385	-3.155498437
8100	2.33	0.695522	-3.15377772
8140	2.30	0.703364	-3.056398333
8170	2.40	0.725076	-2.792335041
8180	2.35	0.718654	-2.869597808
8190	2.37	0.726994	-2.769385081
8200	2.34	0.715596	-2.906637905
8300	2.51	0.751497	-2.481454907
8500	2.64	0.792793	-2.016806133
8700	2.73	0.822289	-1.699508733
10000	3.04	0.926829	-0.660005202
20000	3.23	0.996914	-0.026849758
30000	3.24	0.996923	-0.026767015
40000	3.24	0.997844	-0.018745568
50000	3.24	1	0
60000	3.25	1	0

70000	3.26	1.000614	0.005328767
80000	3.22	1	0

Table 2. Measured data of the parallel RC circuit

In summary, the upper -3 dB frequency (ω_{c1}) is 6000 Hz, the lower -3 dB frequency (ω_{c2}) is 8140 Hz, and the resonant frequency (ω_0) is 7000 Hz.

5) Action 5:

The data has been imported into MATLAB to get the corresponding Bode Plot with frequency in logarithm scale, as shown in Figure 14.

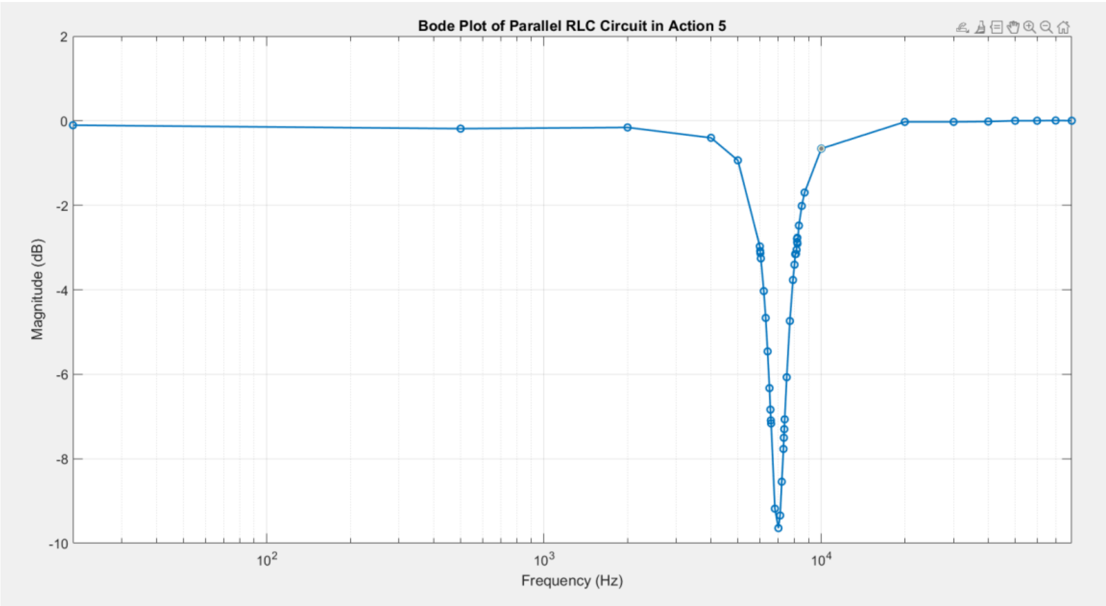

Figure 14: Magnitude Bode plot of the RC circuit

6) Action 6:

✧ **Step 1: Mathematical Derivations**

Apply KVL to the circuit,

$$V_{in} = V_1 + \frac{V_1}{R} \times \frac{\omega L j}{1-\omega^2 CL} \tag{1}$$

The frequency response can be derived as:

$$H(j\omega) = \frac{V_1}{V_{in}} = \frac{1}{1+\frac{\omega L j}{R-R\omega^2 CL}} \tag{2}$$

Take the magnitude of the frequency response:

$$|H(j\omega)| = \frac{1}{\sqrt{1+\frac{\omega^2 L^2}{(R-R\omega^2 CL)^2}}} \tag{3}$$

At the -3dB point,

$$|H(j\omega_c)| = \frac{1}{\sqrt{2}} \times |H(j\omega)|_{max} = \frac{1}{\sqrt{2}} \tag{4}$$

Solving the equation, we obtain two reasonable roots for the corner frequencies:

$$\omega_{c1} = \frac{-1}{2RC} + \sqrt{(\frac{1}{2RC})^2 + \frac{1}{LC}} \tag{5}$$

$$\omega_{c2} = \frac{+1}{2RC} + \sqrt{(\frac{1}{2RC})^2 + \frac{1}{LC}} \tag{6}$$

By performing mathematical operations on these equations above, we can get the experimental capacitance 0.074uF, and the experimental inductance 6.96mH.

	Theoretical value	Measured value
Inductance	6.96mH	4.7mH
Capacitance	0.074uF	0.10uF

Table 3. Comparison of theoretical and measured component characteristics

As we can see from the table, both the inductance and the capacitance show some discrepancies between theoretical and measured values.

✧ **Step 2: Error Analysis**

We attribute the errors to inductor's actual characteristics, which means that we have to consider its intrinsic resistance. The measured resistance of inductor by multimeter is around 12 ohms, so we design a circuit that better approximates the actual scenario to validate our assumptions, as shown in Figure 15.

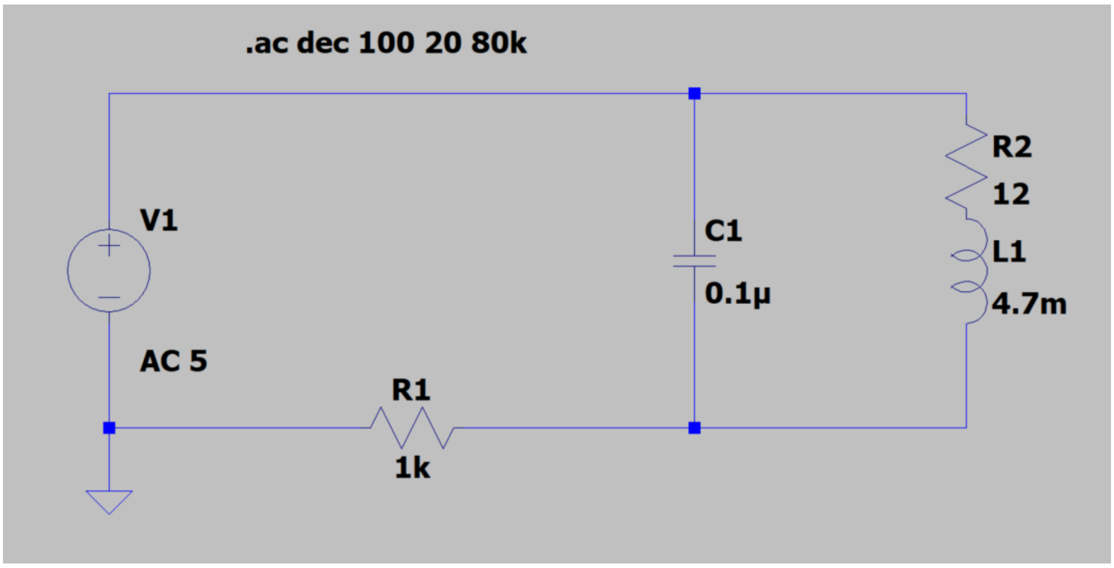

Figure 15: Quasi-actual behavior of inductance in the circuit

Then we draw the Bode plot of this circuit in MATLAB as shown in Figure 16.

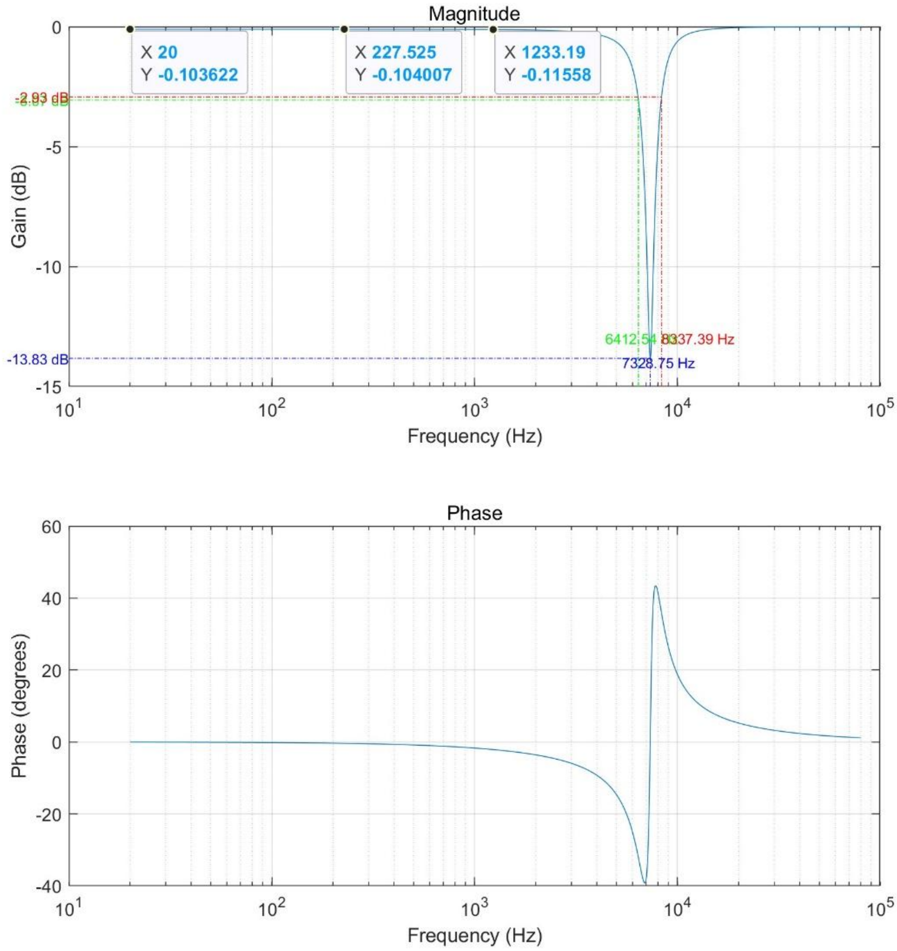

Figure 16: Magnitude and Phase Bode plot of the quasi-actual circuit

The diagrams indicate that the values of $V1/Vin$, ω_c, ω_0 closely match our measurements in low frequencies (approximately 20 Hz), which verifies our hypothesis that inductor's intrinsic resistance will contribute to the errors in capacitance and inductance calculations.

➢ **Part C:**

1) Action 7 (Box 18):

Based on the DC measurement, we can get the following resistance value as the table below:

Resistance between terminals (Ω)		
A&B	A&C	B&D
0.228	999.78	999.79

Table 4. Box terminal resistance under DC measurements of Box 18

Since the resistance between terminal A and B is very small, so it can be treated as a short circuit. Therefore, the components between A and B can only be either an inductor or no component.

If the component is an inductor, the resistance between A and C is slightly larger than that between B and D, so the circuit topology corresponds to the configuration shown in Figure 17.

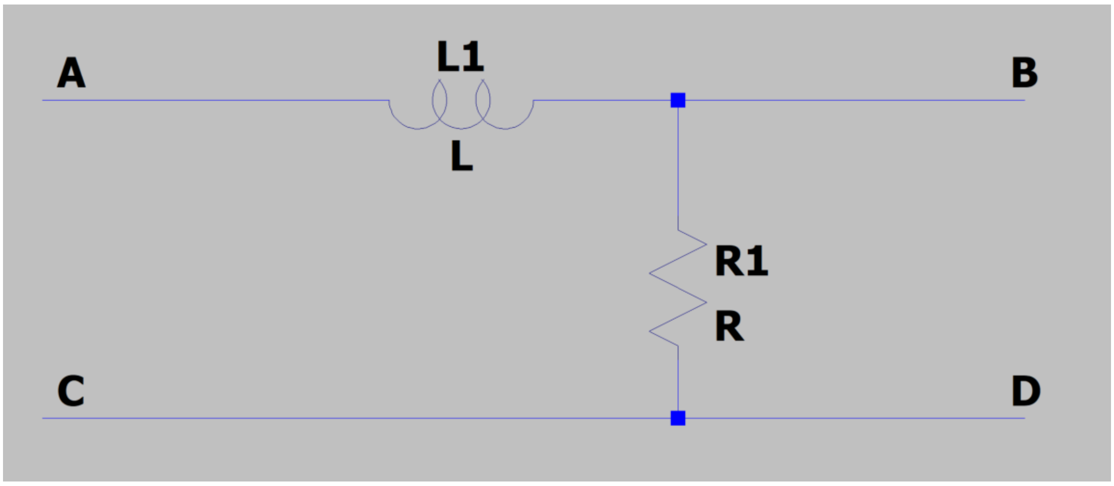

Figure 17: One possible circuit schematic for Box 18

When there is no component between A and B, the circuit topology becomes:

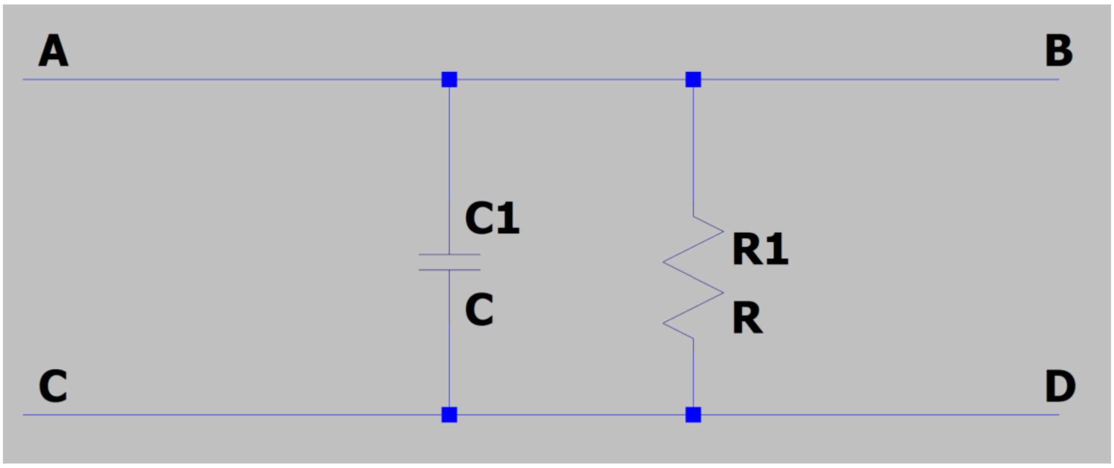

Figure 18: Another possible circuit schematic for Box 18

Note that the relative position of capacitors and resistors has no effect on the experimental results under this circuit topology.

2) Action 8 (Box 18):

- **Discussion of Four Cases in Circuit Determination**

Based on the **AC** measurement, we obtain the following 4 cases which represent BD short, BD open, AC short, AC open respectively.

✧ **Case 1: Experimental Data When BD Is Short-Circuited**

We can design the test circuit as shown in Figure 19.

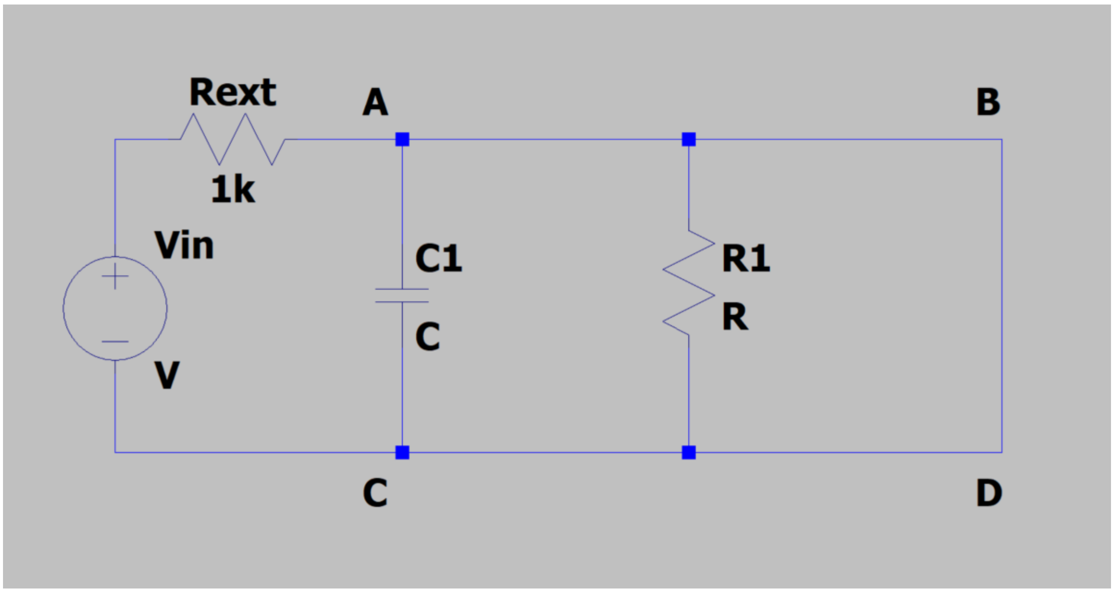

Figure 19: Circuit schematic under BD short-circuited condition

In this circuit, terminals B and D are short-circuited so that the equivalent circuit only has the external resistance.

Then we can get the data with ***V1 and Vin parameters in the table standing for their Root Mean Square (RMS) values*** in Table 5.

Frequency (Hz)	V1(V)	Vin (V)	V1/Vin	20*log10(V1/Vin) (dB)
100	0.001	3.54	0.000282	-70.98006524
500	0.001	3.54	0.000282	-70.98006524
1000	0.001	3.54	0.000282	-70.98006524
1200	0.001	3.54	0.000282	-70.98006524
1300	0.001	3.54	0.000282	-70.98006524
1400	0.001	3.54	0.000282	-70.98006524
1500	0.001	3.54	0.000282	-70.98006524
1600	0.001	3.54	0.000282	-70.98006524
1800	0.001	3.54	0.000282	-70.98006524
3000	0.001	3.54	0.000282	-70.98006524
3500	0.001	3.54	0.000282	-70.98006524
4000	0.001	3.54	0.000282	-70.98006524
5000	0.001	3.54	0.000282	-70.98006524

8000	0.001	3.54	0.000282	-70.98006524
12000	0.001	3.54	0.000282	-70.98006524
16000	0.0011	3.54	0.000311	-70.15221154
20000	0.0011	3.54	0.000311	-70.15221154
80000	0.0027	3.54	0.000763	-62.35278996

Table 5. Experimental data when BD is short circuited

It is evident that V1 hardly changes with frequency variation. However, the impedance of the inductor increases as the frequency rises. **Thus, the former topology is incorrect, indicating that A&B is short circuit.**

✧ Case 2: Experimental Data When BD Is Open-Circuited

We can design the test circuit shown in Figure 20.

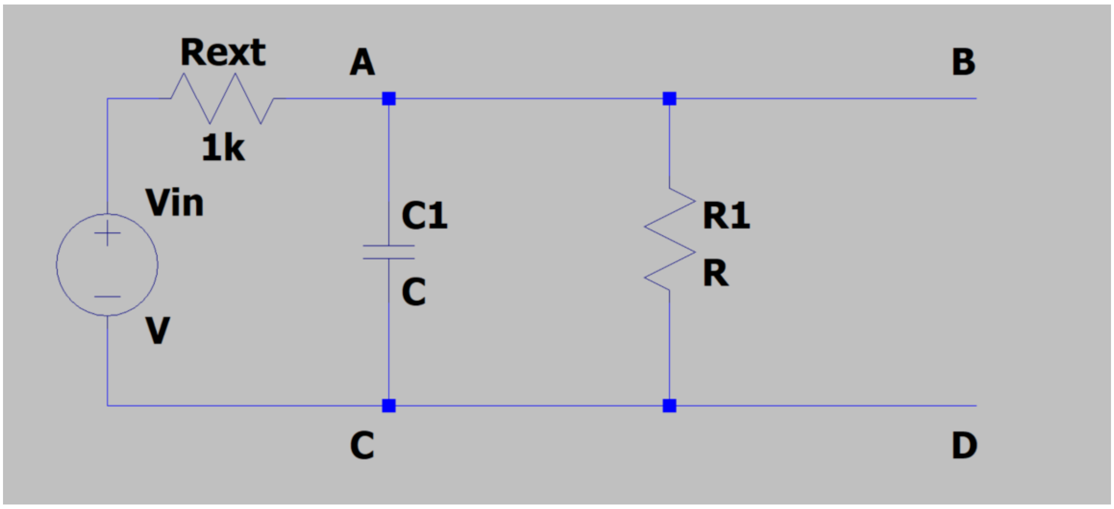

Figure 20: Circuit schematic under BD open-circuited condition

Then we can obtain the data with ***V1 and Vin parameters in the table standing for their Root Mean Square (RMS) values*** in Table 6.

Note that V1 in this circuit represents voltage across A and C.

Frequency (Hz)	V1 (V)	Vin (V)	V1/Vin	20*log10(V1/Vin)
100	1.733	3.54	0.489548	-6.204093986
500	1.709	3.54	0.482768	-6.325223986
1000	1.645	3.54	0.464689	-6.656747195

1200	1.611	3.54	0.455085	-6.838154432
1300	1.593	3.54	0.45	-6.935749724
1400	1.574	3.54	0.444633	-7.03997068
1500	1.554	3.54	0.438983	-7.151044951
1600	1.534	3.54	0.433333	-7.263558048
1800	1.493	3.54	0.421751	-7.498869086
3000	1.234	3.54	0.348588	-9.153762047
3500	1.141	3.54	0.322316	-9.834352352
4000	1.06	3.54	0.299435	-10.47394794
5000	0.913	3.54	0.25791	-11.77064969
8000	0.63	3.54	0.177966	-14.99325425
12000	0.443	3.54	0.125141	-18.05199072
16000	0.339	3.54	0.095763	-20.37607128
20000	0.274	3.54	0.077401	-22.22505398
80000	0.071	3.54	0.020056	-33.95489827

Table 6. Experimental data when BD is open circuited

✧ Case 3: Experimental Data When AC Is Short-Circuited

We can design the test circuit shown in Figure 21.

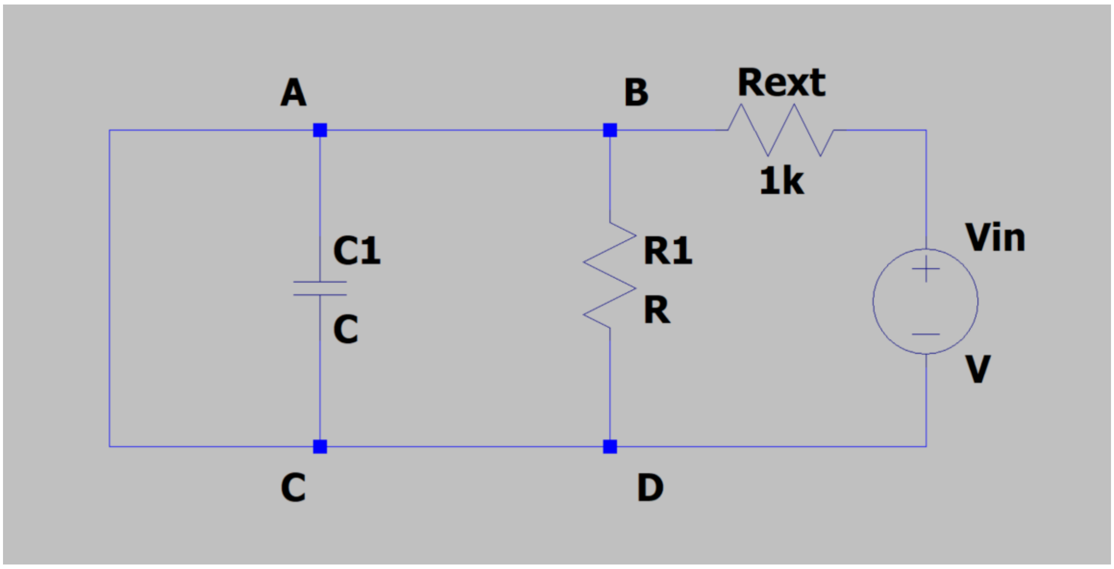

Figure 21: Circuit schematic under AC short-circuited condition

Since terminals A and C are short circuited so that the equivalent circuit only has the external resistance.

Then we can get the data with ***V1 and Vin parameters in the table standing for their Root Mean Square (RMS) values*** in Table 7.

Note that V1 in this circuit represents voltage across A and C.

Frequency (HZ)	V1 (V)	Vin (V)	V1/Vin	20log10(V1/Vin) (dB)
100	0.001	3.54	0.000282	-70.9801
500	0.001	3.54	0.000282	-70.9801
1000	0.001	3.54	0.000282	-70.9801
1200	0.001	3.54	0.000282	-70.9801
1300	0.001	3.54	0.000282	-70.9801
1400	0.001	3.54	0.000282	-70.9801
1500	0.001	3.54	0.000282	-70.9801
1600	0.001	3.54	0.000282	-70.9801
1800	0.001	3.54	0.000282	-70.9801
3000	0.001	3.54	0.000282	-70.9801
3500	0.001	3.54	0.000282	-70.9801
4000	0.001	3.54	0.000282	-70.9801
5000	0.001	3.54	0.000282	-70.9801
8000	0.001	3.54	0.000282	-70.9801
12000	0.001	3.54	0.000282	-70.9801
16000	0.001	3.54	0.000282	-70.9801
20000	0.001	3.54	0.000282	-70.9801
80000	0.002	3.54	0.000565	-64.9595

Table 7. Experimental data when AC is short circuited

It is evident that the statistics are approximately the same as those in Table 5.

✧ **Case 4: Experimental Data When AC Is Open-Circuited**

We can design the test circuit shown in Figure 22.

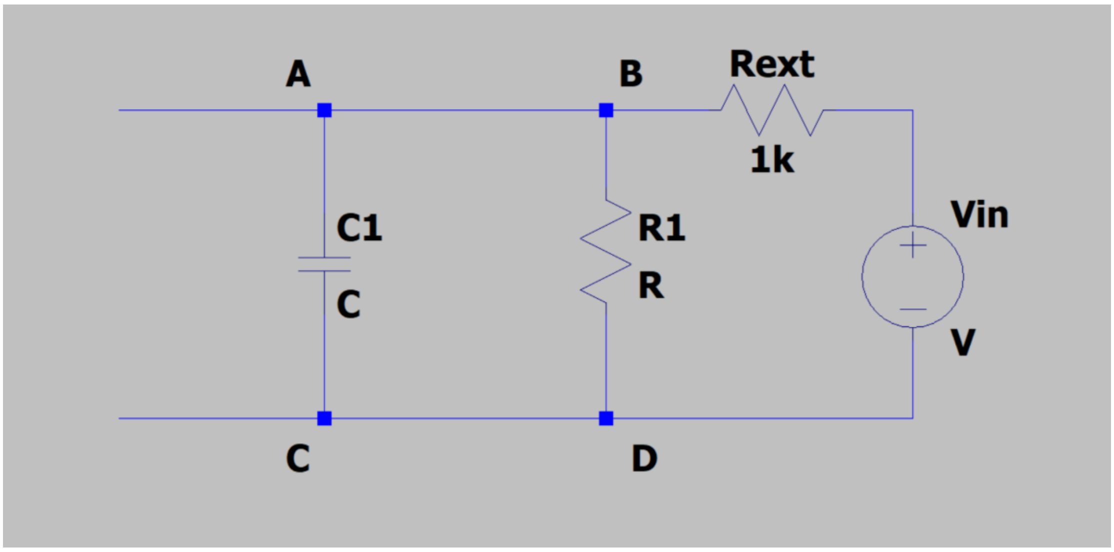

Figure 22: Circuit schematic under AC open-circuited condition

Then we can get the data with ***V1 and Vin parameters in the table standing for their Root Mean Square (RMS) values*** in Table 8.

Note that V1 in this circuit represents voltage across B and D.

Frequency (Hz)	V1 (V)	Vin (V)	V1/Vin	20*log10(V1/Vin) (dB)
100	1.733	3.54	0.489548	-6.204093986
500	1.71	3.54	0.483051	-6.320143033
1000	1.65	3.54	0.466102	-6.630386356
1200	1.612	3.54	0.455367	-6.832764491
1300	1.594	3.54	0.450282	-6.930298899
1400	1.575	3.54	0.444915	-7.034454078
1500	1.555	3.54	0.439266	-7.145457373
1600	1.536	3.54	0.433898	-7.252240927
1800	1.495	3.54	0.422316	-7.487241387
3000	1.246	3.54	0.351977	-9.069704394
3500	1.152	3.54	0.325424	-9.751015659
4000	1.067	3.54	0.301412	-10.41677685
5000	0.923	3.54	0.260734	-11.67603122

8000	0.641	3.54	0.181073	-14.84290465
12000	0.448	3.54	0.126554	-17.95450496
16000	0.343	3.54	0.096893	-20.27418284
20000	0.277	3.54	0.078249	-22.13046986
80000	0.07	3.54	0.019774	-34.07810444

Table 8. Experimental data when AC is open circuited

- **Analysis of Four Cases in Circuit Determination**

✧ **Step1: Bode Plot Analysis under BD Open-Circuited Condition**

Then we draw the BD o/c Bode plot in MATLAB as shown in Figure 23.

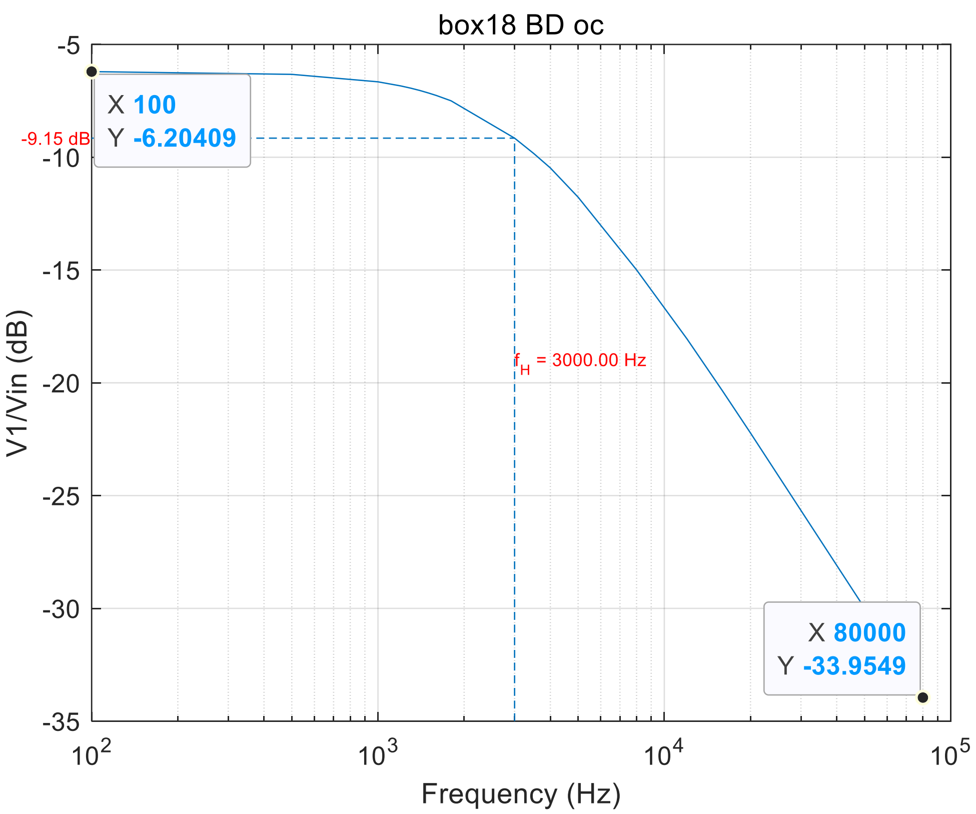

Figure 23: Bode plot of Box 18 under BD open-circuited condition

Since we guess the circuit as the circuit below:

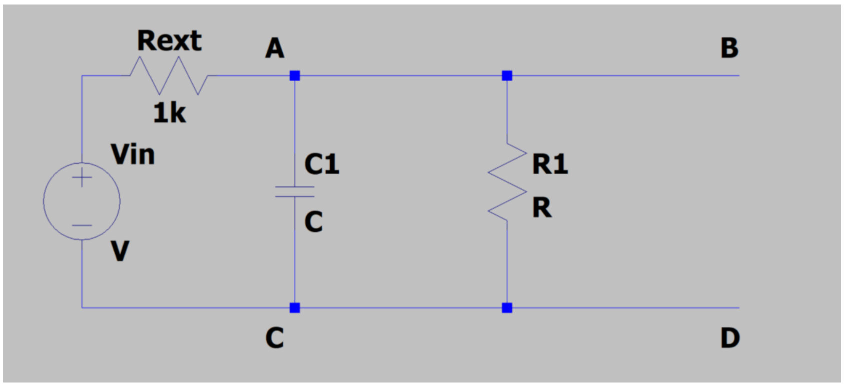

Figure 24: Circuit schematic under BD open-circuited condition

The Bode plot represents the response of the circuit at A-C terminals, which corresponds to the transfer function:

$$H(j\omega) = \frac{V_1}{V_{in}} = \frac{\frac{1}{j\omega c}||R_1}{R_{ext}+\frac{1}{j\omega c}||R_1} = \frac{1}{1+\frac{R_{ext}}{R_1}+j\omega CR_{ext}} \tag{1}$$

When ω is low, the $j\omega CR_{ext}$ part can be neglected, then substitute $|H(j\omega_{low})||_{dB}$ into the formula, where $\omega_{low} = 20\ Hz$ and R_{ext} which have been measured in **Part B**, we have:

$$R_{1_{AC}} = \frac{R_{ext}}{\left(\frac{1}{10^{\frac{|H(j\omega_{low})||_{dB}}{20}}}-1\right)} \approx 948.55\Omega \tag{2}$$

The $R_{1_{AC}}$ is an approximation so We take

$$R_{1_{DC}} = 999.8\ k\Omega \tag{3}$$

As the Final value of R_1

✧ **Step 2: Two methods of capacitance determination**

A. Method 1 for calculating capacitance:

When ω is high, the $1+\frac{R_{ext}}{R_1}$ part can be neglected, then substitute $|H(j\omega_{high})|$ into the formula where $\omega_{high} = 80000\ Hz$ and R_{ext} we have:

$$C = \frac{1}{\omega R_{ext}|H(j\omega_{high})|} = 630.14\ nF \tag{4}$$

This value is not close to the approximate value of C which is $0.1\ \mu F$, so we take another method for calculating the capacitance.

B. Method 2 for calculating capacitance:

Take the amplitude of transfer function below:

$$|H(j\omega)| = \frac{1}{\sqrt{\left(1+\frac{R_{ext}}{R_{1_{DC}}}\right)^2+(\omega C R_{ext})^2}} \tag{5}$$

Change the order of formula we have:

$$C = \frac{\sqrt{\frac{1}{|H(j\omega)|^2}-\left(1+\frac{R_{ext}}{R_{1_{DC}}}\right)^2}}{\omega R_{ext}} \tag{6}$$

We are able to utilize the value of the $R_{1_{DC}}$ measured above for calculate the capacitance,

For $\omega = 1000 \times 2\pi$, $|H(j\omega)| = 0.464689266$

$$C_1 = 261.80\, nF \tag{7}$$

For $\omega = 3000 \times 2\pi$ and $|H(j\omega)| = 0.348587571$

$$C_2 = 134.05\, nF \tag{8}$$

For $\omega = 12000 \times 2\pi$ and $|H(j\omega)| = 0.125141243$

$$C_3 = 105.48\, nF \tag{9}$$

For $\omega = 80000 \times 2\pi$ and $|H(j\omega)| = 0.020056497$

$$C_4 = 100.25\, nF \tag{10}$$

We observe that when the frequency is high, V_{in} decreases. However, this is neglected in action8, which may cause some errors of $|H(j\omega)|$ in higher frequencies, thus we take the first three points which is $\omega = 1000 \times 2\pi$, $\omega = 3000 \times 2\pi$ and $\omega = 12000 \times 2\pi$ to analyze.

As the frequency increases, the effect of the R_1 declines. However, the effect of R_1 cannot be completely neglected when $\omega = 80000 \times 2\pi$, because the value of C has a huge margin of error when using the Method 1 at $80000\ Hz$.

By the analysis above, we take:

$$C_3 = 105.48\ nF \tag{11}$$

as the Final value of the capacitance.

✧ Step 3: Bode Plot Analysis under BD Short-Circuited Condition

The BD s/c Bode plot is presented in Figure 25.

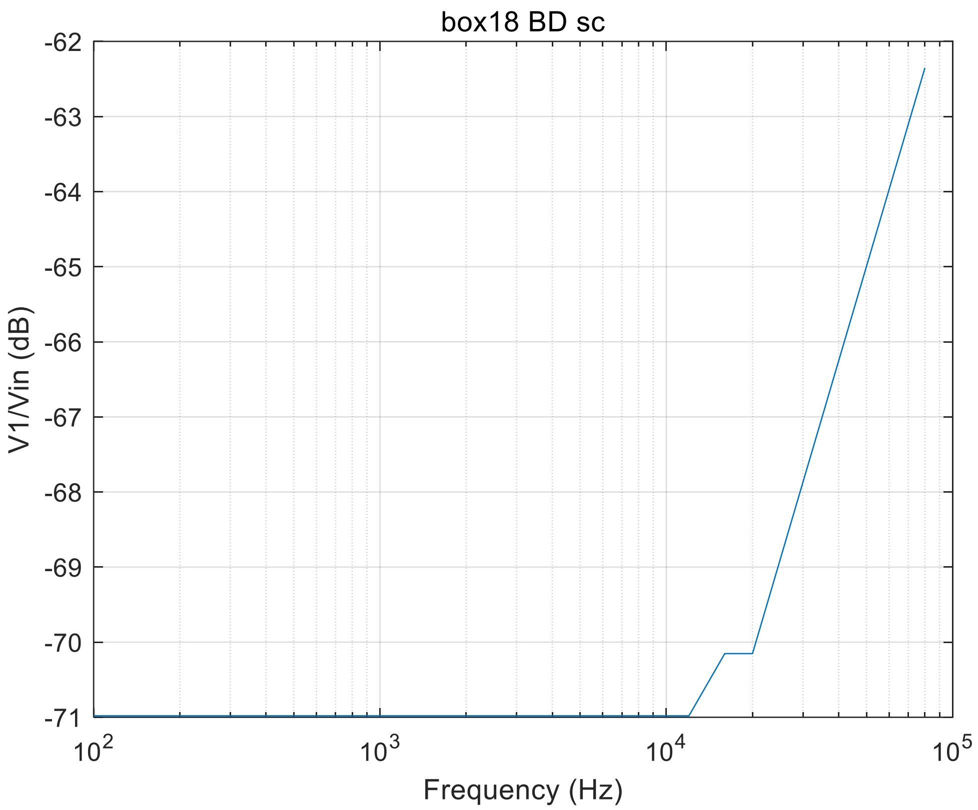

Figure 25: Bode plot of Box 18 under BD short-circuited condition

The general trend of the Bode plot indicates that V_1 is very small with respect to V_{in}. This suggests that AC terminal has no inductance, or the inductance is negligible, because there is still a raise in $10^4\ Hz$. However, the approximate value of the inductance will be used in this experiment is 4.7mH, which will have about:

$$X_{inductance} = 80000\ Hz \times 2\pi \times 4.7\ mH = 2362\Omega > R_{ext} \tag{12}$$

This inductive reactance which will cause significant voltage divider effects when $f = 80000\ Hz$, so in AC terminal there is no inductance which verifies our initial guess of the circuit.

✧ Step 4: Bode Plot Analysis under AC Open-Circuited Condition

The BD AC o/c Bode plot is presented in Figure 26.

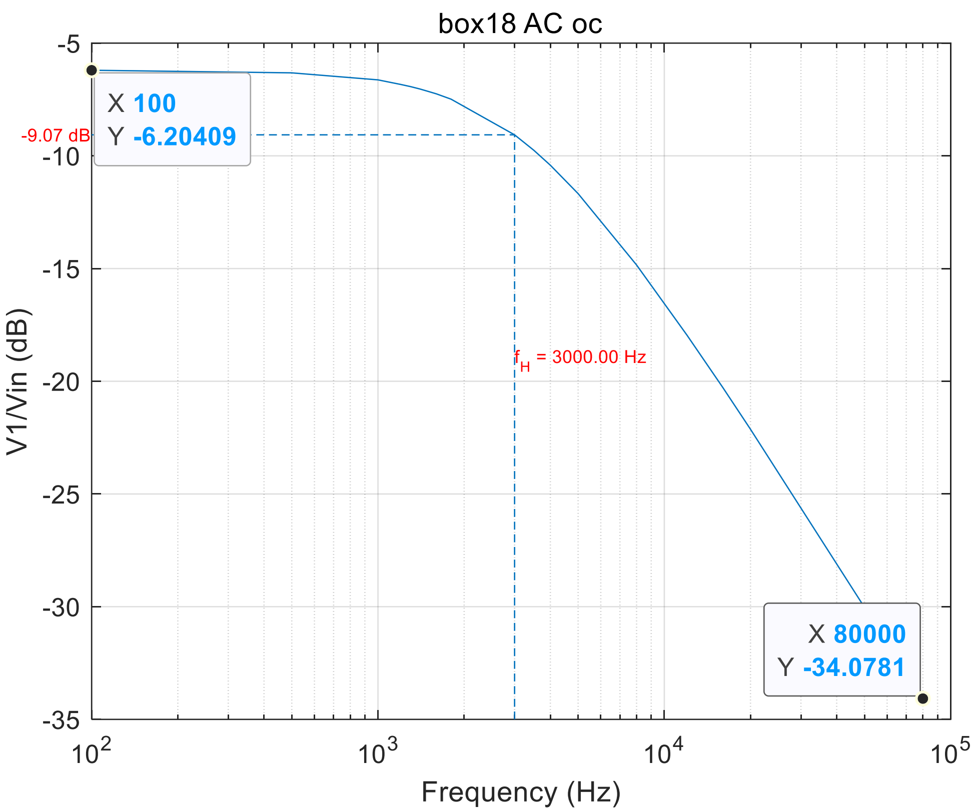

Figure 26: Bode plot of Box 18 under AC open-circuited condition

This is almost the same as the BD o/c situation, which also verifies our initial assumption of the circuit. In other words, the AC o/c situation and the BD o/c situation are expected to be the same, with circuit diagrams under these two situations presented as below.

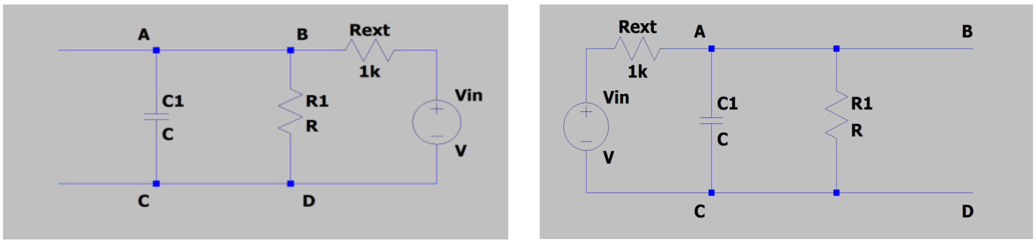

Figure 27: Circuit schematics for AC o/c (left) and BD o/c (right) conditions

V_1 measures the same component in these two circuits, and V_{in} is also the same, thus the Bode plot should be the same.

✧ Step 5: Bode Plot Analysis under AC Short-Circuited Condition

The AC s/c Bode plot is presented in Figure 28.

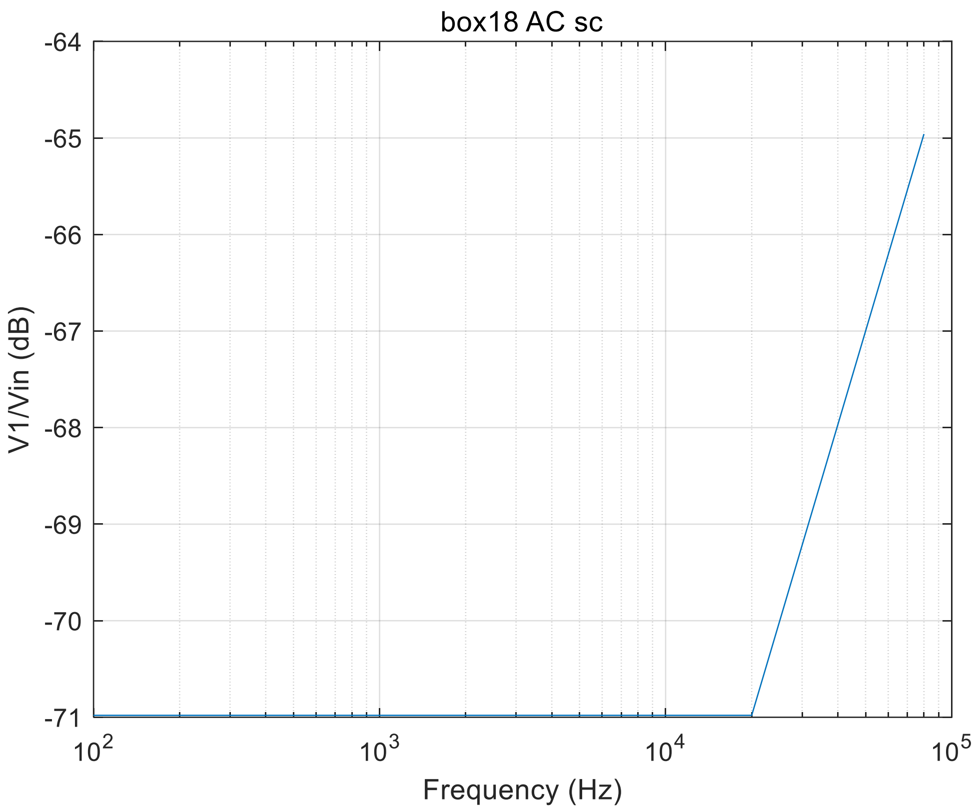

Figure 28: Bode plot of Box 18 under AC short-circuited condition

This Bode plot is also similar to that in BD s/c situation, the reason has been declared in "AC o/c Bode plot" analysis.

In summary, the Final topology is:

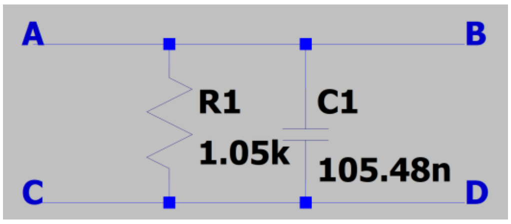

Figure 29: One circuit schematic of Box 18

Or

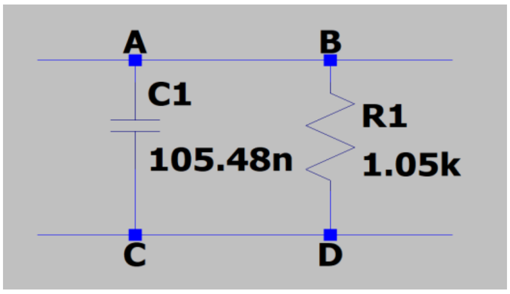

Figure 30: Another circuit schematic of Box 18

3) Action 9 (Box 25):

Bode plots under 4 different cases are presented as below.

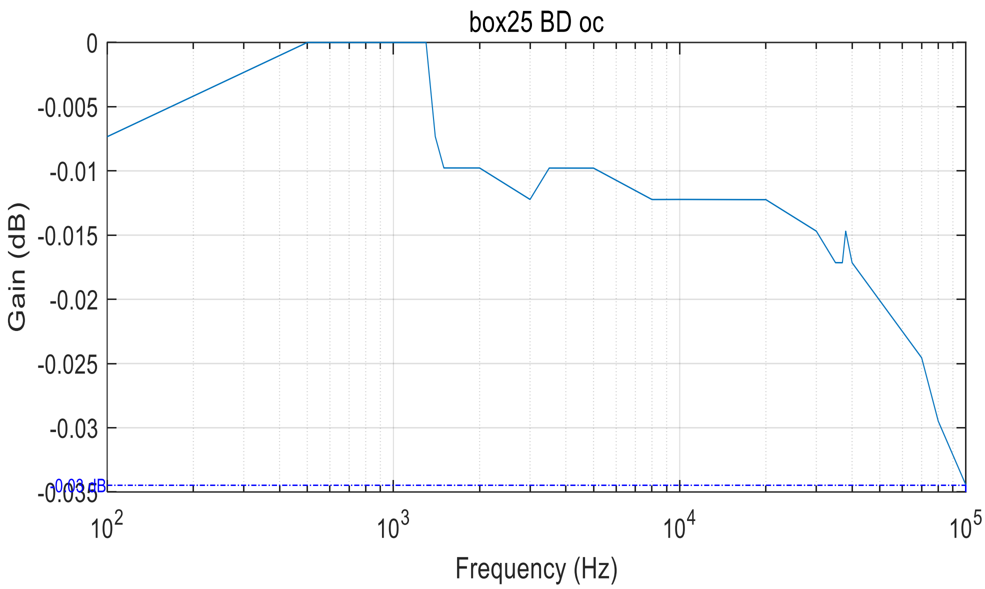

Figure 31: BD o/c Bode plot of Box 25

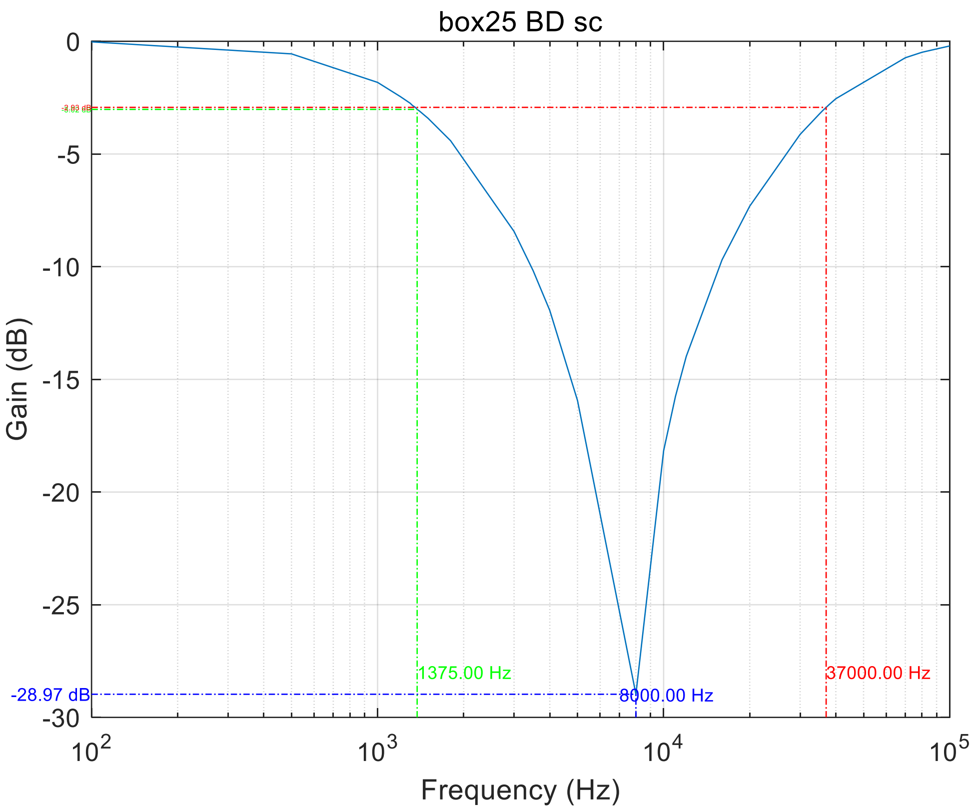

Figure 32: BD s/c Bode plot of Box 25

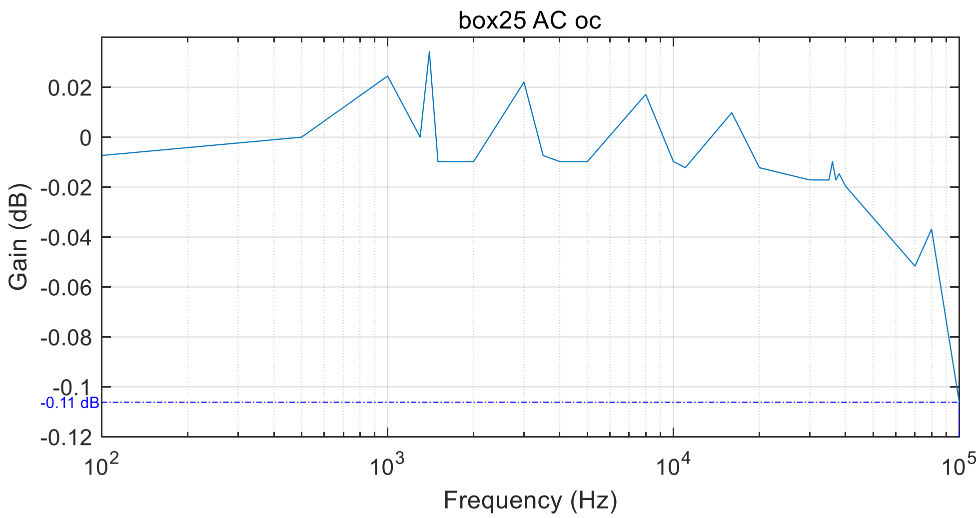

Figure 33: AC o/c Bode plot of Box 25

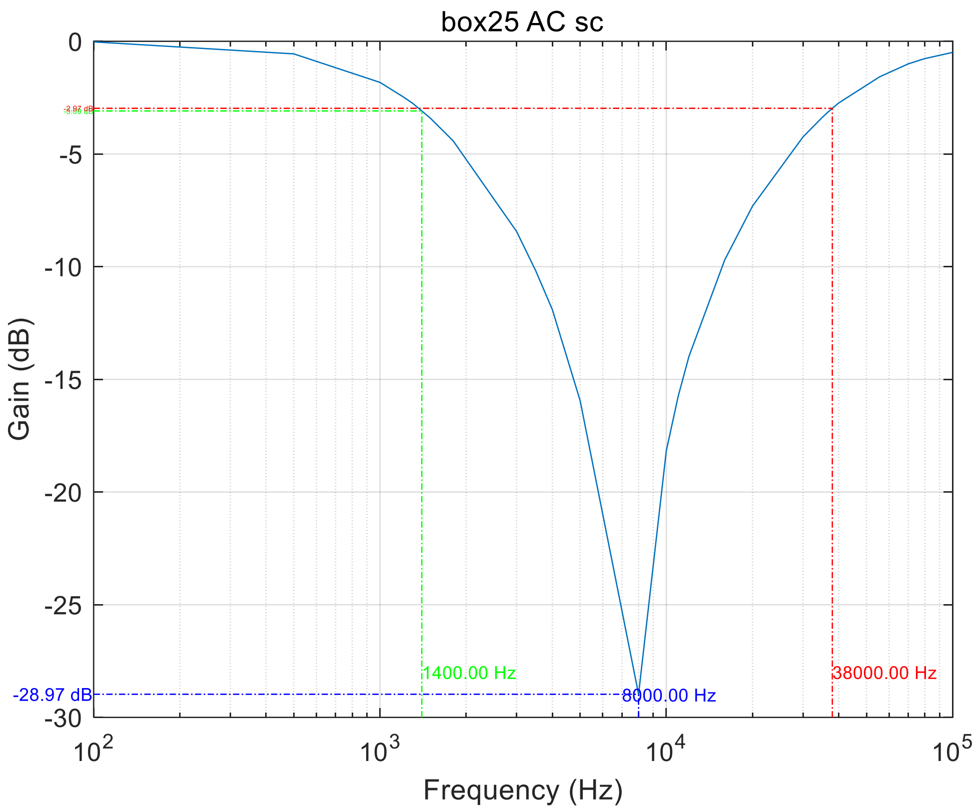

Figure 34: AC s/c Bode plot of Box 25

Combined with DC and AC analysis, the Final topology of Box 25 is:

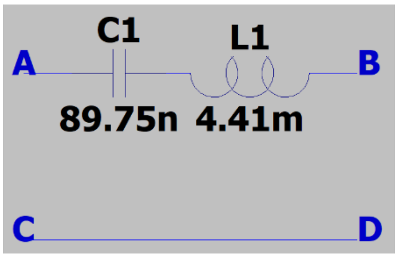

Figure 35: One possible circuit schematic for Box 25

Or

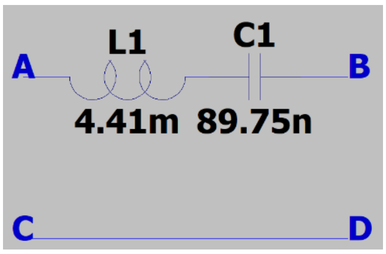

Figure 36: One possible circuit schematic for Box 25

Appendix:

Resistance between terminals (Ω)		
A&B	A&C	B&D
over	over	over

Table 9. Box terminal resistance under DC measurements of Box 25

Frequency (HZ)	V1 (V)	Vin (V)	V1/Vin	20log10(V1/Vin) (dB)
100	3.53	3.54	0.997175	-0.024571133
500	3.32	3.54	0.937853	-0.557303566
1000	2.87	3.54	0.810734	-1.822427306
1200	2.67	3.54	0.754237	-2.449840013
1300	2.58	3.54	0.728814	-2.747671121
1325	2.55	3.54	0.720339	-2.849261632
1350	2.53	3.54	0.714689	-2.917654817
1365	2.515	3.54	0.710452	-2.969305453
1375	2.5	3.54	0.706215	-3.021265067
1400	2.48	3.54	0.700565	-3.091031624
1500	2.39	3.54	0.675141	-3.412107222
1800	2.13	3.54	0.601695	-4.412473172
3000	1.34	3.54	0.378531	-8.437969273
3500	1.096	3.54	0.309605	-10.18385416
4000	0.895	3.54	0.252825	-11.94360453
5000	0.565	3.54	0.159605	-15.93909628
8000	0.126	3.54	0.035593	-28.97265434
10000	0.437	3.54	0.123446	-18.1704365
11000	0.577	3.54	0.162994	-15.75654898
12000	0.708	3.54	0.2	-13.97940009
16000	1.159	3.54	0.327401	-9.698396521

20000	1.525	3.54	0.430791	-7.314668367
30000	2.2	3.54	0.621469	-4.131611624
35000	2.44	3.54	0.689266	-3.232268714
36000	2.485	3.54	0.701977	-3.073537379
37000	2.526	3.54	0.713559	-2.931398316
38000	2.566	3.54	0.724859	-2.7949322
40000	2.64	3.54	0.745763	-2.547986703
70000	3.255	3.54	0.919492	-0.729045382
80000	3.347	3.54	0.94548	-0.486950993
100000	3.457	3.54	0.976554	-0.20607765

Table 10. Experimental data when BD is short circuited of Box 25

Frequency (HZ)	V1 (V)	Vin (V)	V1/Vin	20log10(V1/Vin) (dB)
100	3.55	3.553	0.999156	-0.007337089
500	3.553	3.553	1	0
1000	3.553	3.553	1	0
1300	3.553	3.553	1	0
1400	3.554	3.557	0.999157	-0.007328834
1500	3.554	3.558	0.998876	-0.009770406
2000	3.553	3.557	0.998875	-0.009773154
3000	3.551	3.556	0.998594	-0.0122216
3500	3.551	3.555	0.998875	-0.009778655
4000	3.55	3.554	0.998875	-0.009781408
5000	3.549	3.553	0.998874	-0.009784163
8000	3.549	3.554	0.9986	-0.012228482
10000	3.551	3.556	0.998594	-0.0122216
11000	3.55	3.555	0.998594	-0.01222504
16000	3.547	3.552	0.998592	-0.012235373
20000	3.546	3.551	0.998592	-0.012238821

30000	3.545	3.551	0.99831	-0.014688656
35000	3.543	3.55	0.998028	-0.017144014
37000	3.542	3.549	0.998028	-0.01714885
38000	3.543	3.549	0.998309	-0.01469694
40000	3.542	3.549	0.998028	-0.01714885
70000	3.533	3.543	0.997178	-0.024550298
80000	3.529	3.541	0.996611	-0.029485368
100000	3.52	3.534	0.996038	-0.034477634

Table 11. Experimental data when BD is open circuited of Box 25

Frequency (HZ)	V1 (V)	Vin (V)	V1/Vin	20log10(V1/Vin) (dB)
100	3.53	3.54	0.997175	-0.024571133
500	3.32	3.54	0.937853	-0.557303566
1000	2.87	3.54	0.810734	-1.822427306
1200	2.67	3.54	0.754237	-2.449840013
1300	2.58	3.54	0.728814	-2.747671121
1400	2.48	3.54	0.700565	-3.091031624
1500	2.39	3.54	0.675141	-3.412107222
1800	2.13	3.54	0.601695	-4.412473172
3000	1.34	3.54	0.378531	-8.437969273
3500	1.096	3.54	0.309605	-10.18385416
4000	0.899	3.54	0.253955	-11.90487141
5000	0.565	3.54	0.159605	-15.93909628
8000	0.126	3.54	0.035593	-28.97265434
10000	0.437	3.54	0.123446	-18.1704365
11000	0.577	3.54	0.162994	-15.75654898
12000	0.708	3.54	0.2	-13.97940009
16000	1.159	3.54	0.327401	-9.698396521
20000	1.525	3.54	0.430791	-7.314668367

30000	2.171	3.54	0.613277	-4.246868771
35000	2.398	3.54	0.677401	-3.383081665
36000	2.438	3.54	0.688701	-3.239391215
37000	2.477	3.54	0.699718	-3.101545109
38000	2.514	3.54	0.710169	-2.972759774
40000	2.583	3.54	0.729661	-2.737577117
55500	2.951	3.54	0.833616	-1.580681051
70000	3.155	3.54	0.891243	-1.000077969
80000	3.241	3.54	0.915537	-0.76648462
100000	3.345	3.54	0.944915	-0.492142798

Table 12. Experimental data when AC is short circuited of Box 25

Frequency (HZ)	V1 (V)	Vin (V)	V1/Vin	20log10(V1/Vin) (dB)
100	3.551	3.554	0.999156	-0.007335023
500	3.553	3.553	1	0
1000	3.55	3.54	1.002825	0.024501821
1300	3.553	3.553	1	0
1400	3.554	3.54	1.003955	0.034283229
1500	3.554	3.558	0.998876	-0.009770406
2000	3.553	3.557	0.998875	-0.009773154
3000	3.549	3.54	1.002542	0.022054746
3500	3.552	3.555	0.999156	-0.007332959
4000	3.55	3.554	0.998875	-0.009781408
5000	3.549	3.553	0.998874	-0.009784163
8000	3.547	3.54	1.001977	0.017158529
10000	3.552	3.556	0.998875	-0.009775904
11000	3.55	3.555	0.998594	-0.01222504
16000	3.544	3.54	1.00113	0.009809024
20000	3.546	3.551	0.998592	-0.012238821

30000	3.544	3.551	0.998029	-0.017139182
35000	3.543	3.55	0.998028	-0.017144014
36000	3.536	3.54	0.99887	-0.009820114
37000	3.542	3.549	0.998028	-0.01714885
38000	3.543	3.549	0.998309	-0.01469694
40000	3.541	3.549	0.997746	-0.019601452
70000	3.519	3.54	0.994068	-0.051679904
80000	3.528	3.543	0.995766	-0.036851517
100000	3.497	3.54	0.987853	-0.106152594

Table 13. Experimental data when AC is open circuited of Box 25