Report: Time-Domain and Frequency-Domain Analyses in LTSpice

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EE202-03 Lab 1

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Purpose:

In this lab, the LTSpice tool and time-domain and frequency-domain analysis have been covered. Additionally, OPAMP circuits have been introduced on top of simple circuit elements.

Software Implementation:

Introduction:

This lab contains performing time-domain and frequency-domain analyses in LTSpice in a series of circuits and creating and analyzing OPAMP circuits. The lab contains three parts as following:

- Part 1: Transient (time-domain) Analysis
- Part 2: AC (frequency-domain) Analysis
- Part 3: OPAMP Circuits

In each part, there are necessary steps to be taken, and those steps have been taken diligently. Since specific to this lab, it does not require any mathematical support for the decisions we will make. It will be continued with the analysis part.

Analysis:

For the analysis section, each part will be investigated and discussed separately.

Part 1: Transient (time-domain) Analysis

The values of this part have been chosen as follows:

- Here are the values,
  - R_1: 5Ω
  - R_2: 20Ω
  - V_1: 10V
  - Frequency of V1: 10kHz

Since it is a simple series resistor circuit, we can apply the voltage divider formula to find the voltage on R_2. Let V_{R_2} be the voltage on R_2.

$$V_{R_2} = \frac{V_1 R_2}{R_1 + R_2}$$

For the second step of this part, the inductor will be inserted in the place of R_2 resistor. To proceed with this step, these values have been chosen:

- Values are,
  - R_1: 50Ω
  - L_1: 100μH
  - V_1: 5V
  - Frequency of V1: 10kHz-100kHz-500kHz

Due to excitation being sinusoidal, signal phasor analyses have been performed.

- For ω=10kHz

$$X_{L_1} = j\omega L = j(10^4 s^{-1})(10^{-4} H) = j\Omega$$

$$Z_1 = R_1 + X_L = 50 + j$$

- For ω=100kHz

$$X_{L_2} = j\omega L = j(10^5 s^{-1})(10^{-4} H) = j10\Omega$$

$$Z_2 = R_1 + X_L = 50 + j10$$

- For ω=500kHz

$$X_{L_3} = j\omega L = j(5 * 10^5 s^{-1})(10^{-4}H) = j50\Omega$$

$$Z_3 = R_1 + X_L = 50 + j50$$

At the current state voltage divider formula can be applied so, that V_L voltage across the inductor is following assuming that $V_1 = 5cos(\omega t)V$,

- For ω=10kHz

$$V_L = \frac{V_1 X_{L_1}}{Z_1} = \frac{5 * j}{50 + j} = 0.002 + j0.1 \Rightarrow V_L(t) = 0.1cos(\omega t + 88.51°)V$$

- For ω=100kHz

$$V_L = \frac{V_1 X_{L_2}}{Z_2} = \frac{5 * j10}{50 + j10} = 0.96 + j0.19 \Rightarrow V_L(t) = 0.98cos(\omega t + 11.45°)V$$

- For ω=500kHz

$$V_L = \frac{V_1 X_{L_3}}{Z_3} = \frac{5 * j50}{50 + j50} = 2.5 + j2.5 \Rightarrow V_L(t) = 3.54cos(\omega t + 45.0°)V$$

This circuit is a high-pass filter since as ω increases, X_L will go to infinity so that circuit will be open circuit, and for small frequency, the inductor act as a short circuit.

Part 2: AC (frequency-domain) Analysis

Now AC analysis will be conducted to observe the behavior of the circuit in a frequency range. The values of this part have been chosen as follows:

- Here are the values,
  - R_1: 50Ω
  - R_2: 50Ω (in 2nd step)
  - L_1: 100μH
  - V_1: 1V small signal

To have an idea of the graph in simulation, one may find the transfer function of the circuit.

- For R_2=0Ω

$$H(\omega) = \frac{V_L}{V_1} = \frac{\frac{V_1 j\omega L}{R_1 + j\omega L}}{V_1} = \frac{j\omega L}{R_1 + j\omega L}$$

$$|H(\omega)|_{dB} = 20log(|H(\omega)|)$$

- For R_2=50Ω

$$H(\omega) = \frac{V_L}{V_1} = \frac{\frac{V_1 j\omega L}{R_1+R_2+j\omega L}}{V_1} = \frac{j\omega L}{R_1 + R_2 + j\omega L}$$

$$|H(\omega)|_{dB} = 20log(|H(\omega)|)$$

By adding R_2=50Ω more realistic behavior has been simulated and compared with the results coming from the R_2=0Ω version. After investigating the transfer functions of both circuits, one can conclude that the second high-pass filter passes higher frequencies compared to the first circuit.

Part 3: OPAMP Circuits

In OPAMP part lab work requires to create an inverter amplifier and integrator amplifier. Following values are before the saturation, and R_2' is the latter value of the resistor to saturate the OPAMP. For the integrator circuit, resistor R_2 will be changed with capacitor C_1, and the resistor R_1 will be changed to R_1'.

- Values are,
  - R_1: 500Ω
  - R_1': 8kΩ
  - R_2: 2kΩ
  - R_2': 8kΩ
  - R_3: 1kΩ
  - C_1: 3nF

To find the V_{out} the voltage on the exit of OPAMP, one may write a nodal analysis. Nodal analysis on V^- leg of the OPAMP.

$$\frac{V^- - V_1}{R_1} + \frac{V^- - V_{out}}{R_2} = 0$$

Since inverter OPAMP is in linear state $V^+ = V^- = 0V$.

$$\frac{-V_1}{R_1} + \frac{-V_{out}}{R_2} = 0 \Rightarrow V_{out} = -\frac{R_2}{R_1}V_1 \Rightarrow V_{out} = -4V_1$$

And to satisfy linear state one writes the following inequality,

$$-10 < V_{out} < 10 \Rightarrow -10 < -\frac{R_2}{R_1}V_1 < 10$$

For the next step, it requires saturating the OPAMP, and for this reason, R_2 is chosen as $8k\Omega$ with $V_1 = 1V$

$$-10 < V_{out} < 10 \Rightarrow -10 < -\frac{R_2}{R_1}V_1 < 10 \Rightarrow -10 < -\frac{8000}{500}V_1 < 10$$

$$\Rightarrow -10 < -16V_1 < 10$$

Finally, for the integrator OPAMP, one can write a similar nodal analysis. Note that $\frac{dV_C}{d_t} = \frac{i_C}{C}$ where $V_C = V^- - V_{out}$. Then nodal analysis from V^- can be written as,

$$\frac{V^- - V_1}{R_1} + C\frac{d(V^- - V_{out})}{dt} = 0 \Rightarrow \frac{-V_1}{R_1} - C\frac{dV_{out}}{dt} = 0$$

$$\Rightarrow V_{out}(t) = -\frac{1}{R_1C}\int V_1(t)dt$$

From here, one can see that for a square wave of V_1 the output of the OPAMP will be triangles like a saw tooth and after inserting the numbers of the capacitor and resistor,

$$V_{out}(t) = -\frac{1}{R_1C}\int V_1(t)dt \Rightarrow V_{out}(t) = -\frac{1}{8000 * 3 * 10^{-9}}\int V_1(t)dt$$

$$\Rightarrow V_{out}(t) = -\frac{10^6}{24}\int V_1(t)dt$$

Simulation:

As done in the analysis section in the simulation part, a similar approach will be followed to investigate and discuss each part. The following figures include the implementation on the LTSpice tool from the previously explained analysis part.

Note that the figures below may seem little, but since they are high quality, the reader may zoom in as much as they wish. The size of the figures is as they are just because of aesthetic concerns. If plots are not as visible as required, please kindly zoom in.

Part 1: Transient (time-domain) Analysis

The below figures include the simulations on the LTSpice,

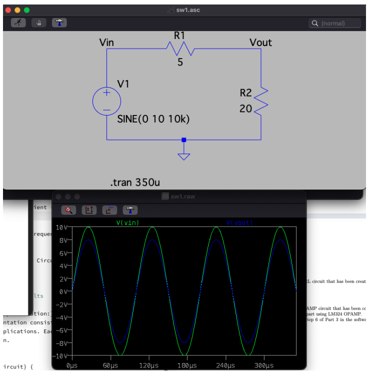
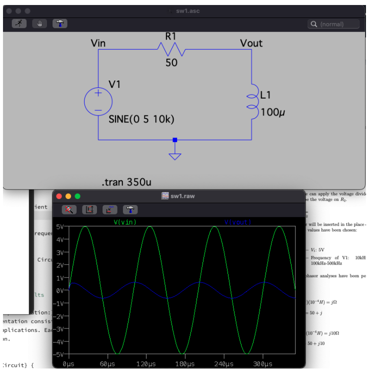
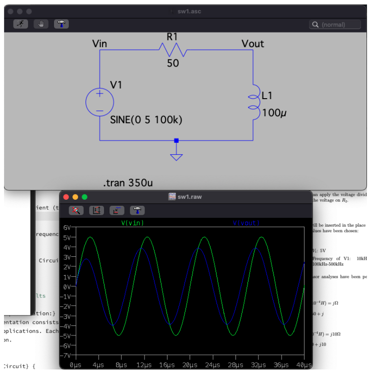


Figure 1: Transient state with voltage divider demo.

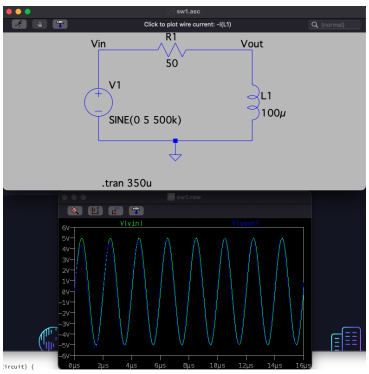
Simulation figures from the high-pass filter circuit,



(a) Input frequency 10kHz.



(b) Input frequency 100kHz.



(c) Input frequency 500kHz.

Figure 2: High-pass circuit simulation.

Part 2: AC (frequency-domain) Analysis

The below figures include the simulations for AC analysis on the LTSpice tool, first figure is the frequency analysis of the circuit on a logarithmic scale.

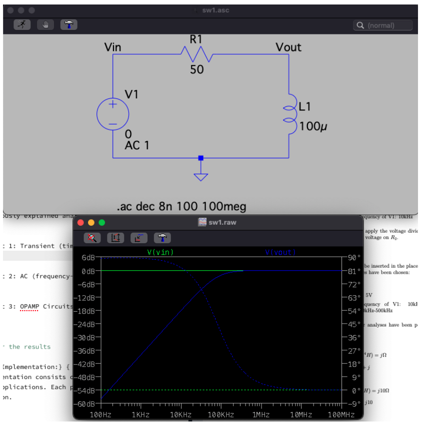


Figure 3: Transient state with voltage divider demo.

In the second figure, there is an extra $R_2 = 50\Omega$ to simulate a real voltage source.

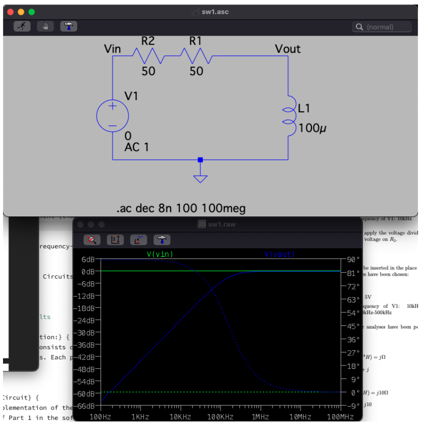
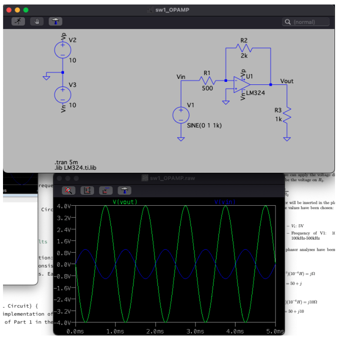


Figure 4: Transient state with voltage divider demo.

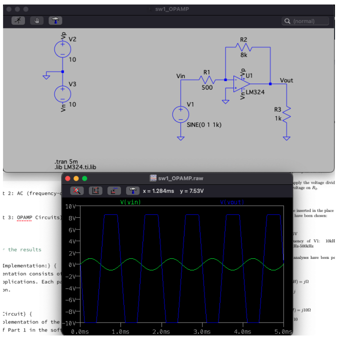
As one can see from the graphs, after adding the second resistor, the graph has been shifted to the right, which means the high-pass filter passes higher frequencies compared to the first circuit.

Part 3: OPAMP Circuits

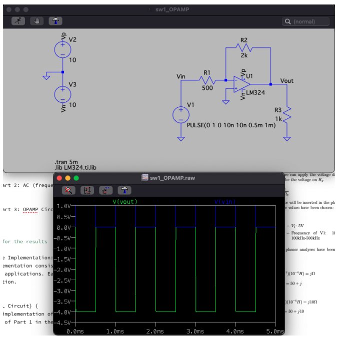
The below figures include the simulations for the OPAMP circuit,



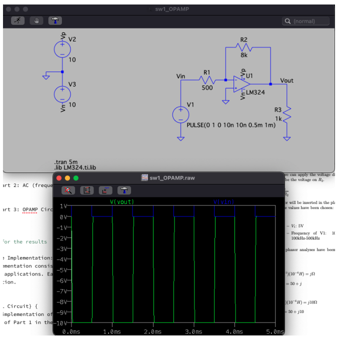
(a) Sinusoidal signal not-saturated.



(b) Sinusoidal signal saturated.



(c) Square wave signal not-saturated.



(d) Square wave signal saturated.

Figure 5: Inverter OPAMP circuit.

After adding a capacitor and creating an integrator OPAMP,

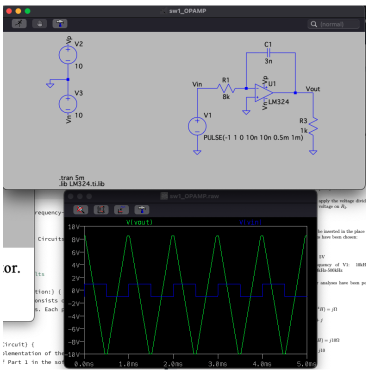


Figure 6: Integrator OPAMP circuit.

Hardware Implementation:

The hardware implementation consists of the above-described software results' applications. Each part has its own section for necessary information.

RL Circuit

This part is the implementation of the RL circuit that has been created in Step 2 of Part 1 from the software section.

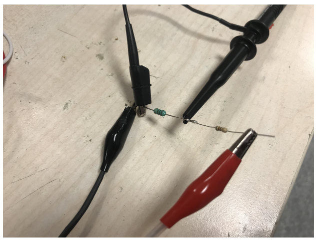
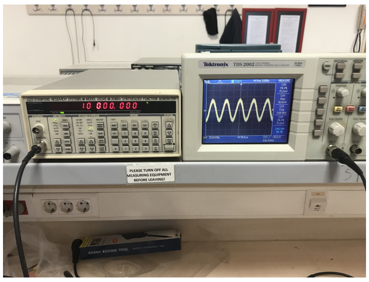
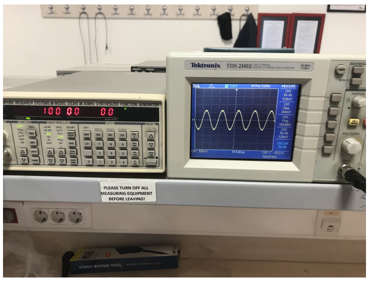


Figure 7: RL circuit itself.

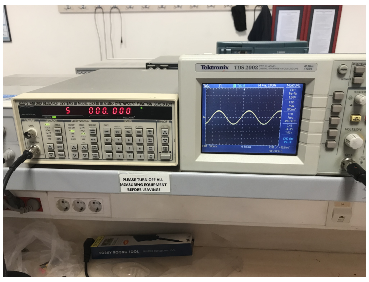
After changing the voltage source's frequency to 10kHz, 100kHz, and 500kHz.



(a) Input frequency 10kHz.



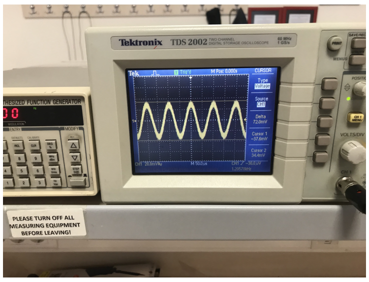
(b) Input frequency 100kHz.



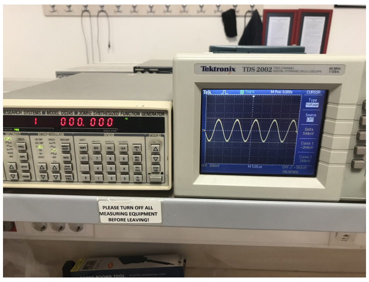
(c) Input frequency 500kHz.

Figure 8: High-pass circuit implementation.

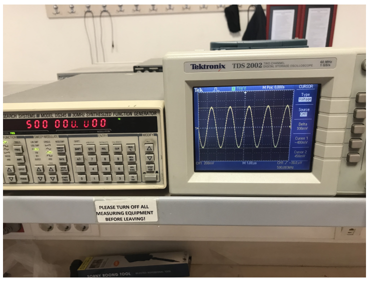
The cursor indicated voltages in different frequencies.



(a) Input frequency 10kHz and gain -23.35dB



(b) Input frequency 100kHz and gain -5.03dB



(c) Input frequency 500kHz and gain -0.80dB

Figure 9: High-pass circuit implementation and gain calculation.

Frequency	Theoritical Gain (dB)	Experimental Gain (dB)
10kHz	-21.94	-23.35
100kHz	-4.43	-5.03
500kHz	-0.17	-0.80

Table 1: Table of gain comparison between theoretical and experimental.

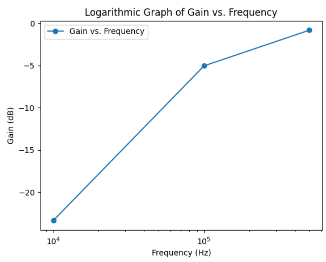


Figure 10: Rough plot of the experimental data points.

OPAMP Circuit

This part is the implementation of the OPAMP circuit that has been constructed in Step 3 of Part 3 from the software part using LM324 OPAMP.

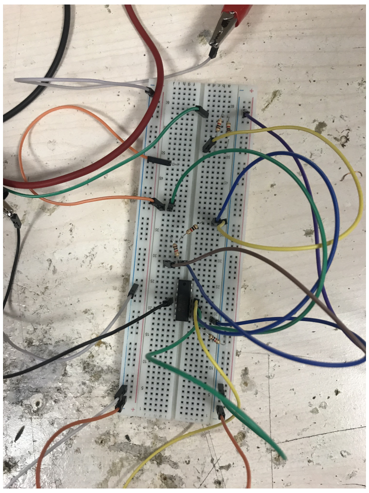


Figure 11: Inverter OPAMP circuit itself.

The observation of $V_{out} = -4V_1$ by oscilloscope,

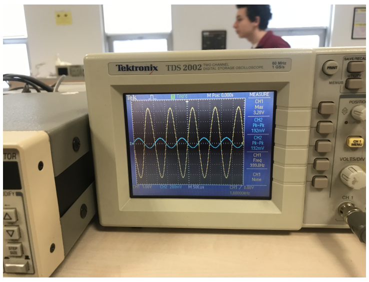


Figure 12: Inverter OPAMP circuit and $V_{out} = -4V_1$

Input Voltage	Theoretical Output Voltage	Experimental Output Voltage
1V	-4V	-3.19V

Table 2: Inverter OPAMP table.

The integrator OPAMP part from the Step 6 of Part 3 in the software component.

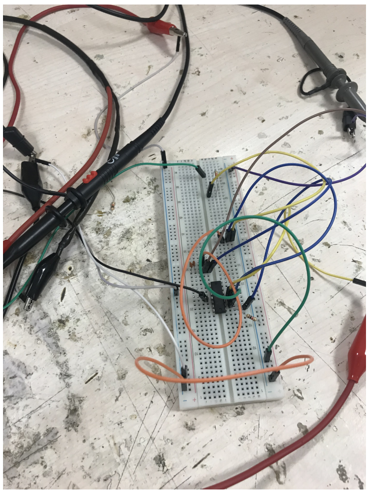


Figure 13: Integrator OPAMP circuit itself.

The observation of triangular output by oscilloscope,

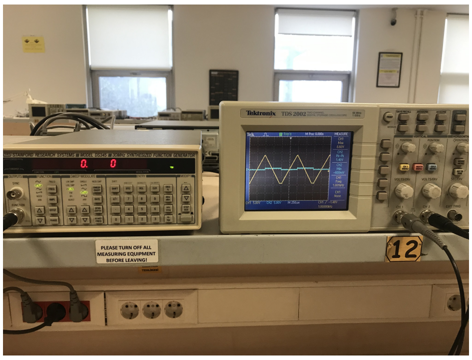


Figure 14: Integrator OPAMP circuit and oscilloscope

Conclusion:

In summary, the hardware and software components overlap in the experiments conducted on the high pass filter (RL circuit), where the output voltage decreases as the frequency decreases. Although the gains for frequencies of 10Khz, 100Khz, and 500 Khz are marginally lower than the simulations, this difference can be explained by the small discrepancy between the simulations and hardware such as the resistor and inductor values also

the resistance of cables between circuit elements may have been cause small errors in the output voltage V_{out}.
When it comes to inverter OPAMP part to achieve a ratio of $V_{out} = -4V_1$ in the inverter, it has been used 512Ω instead of 500Ω and 50Ω instead of 100Ω, since the signal source has 50Ω internal resistance. The V_{out} values obtained in the software and hardware parts were slightly different, which may be due to the use of a breadboard, which can cause resistance in the cables and capacitance between the metal plates and plastic of the breadboard.
In the integrator, an equation was used to calculate V_{out}, and the values obtained in the software and hardware parts have lightl differed, but this error was also negligible.
In conclusion, the experiments demonstrated the use of OPAMP for mathematical operations and RL circuit for high-pass filters. Additionally, different simulation methods such as transient (time-domain) analysis and AC (frequency-domain) analysis were learned.

References:

- Analog Electronics, A. Atalar, Accessed from Moodle.