Passive High-Pass Filter

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***Abstract*—This report details the design, implementation, and analysis of a passive third-order LC high-pass filter for biomedical signal applications. The filter was derived from normalized Butterworth low-pass filter values and transformed into a high-pass configuration with a target cutoff frequency of 1 kHz. Experimental measurements and LTSpice simulations were conducted to characterize the frequency response and roll-off behavior. The measured cutoff frequency closely matched the design, though discrepancies in roll-off rate were observed, likely due to limitations in available equipment. Results confirm the filter's suitability for removing low-frequency artifacts.**

***Index Terms*—High-Pass, Bioinstrumentation, Filter Design**

I. Introduction

In physiological signal acquisition systems, such as ECG, EMG, or EEG, filtering is critical to isolate the desired biosignals from low-frequency noise and interference, including motion artifacts and baseline drift. A high-pass filter is particularly useful for eliminating these unwanted low-frequency components while preserving the integrity of higher-frequency biomedical signals. The third-order filter offers enhanced selectivity and steeper roll-off compared to lower-order designs, making it suitable for applications requiring precise frequency discrimination.

The ladder or Pi configuration of the filter illustrated in Fig. 1 is a common design choice for high-pass filters, as it provides a compact and efficient layout.

II. Methodology

A. Design Process

From "Table A-1 Element values for low-pass single-resistance-terminated lossless-ladder realizations" in *Introduction to the Theory and Design of Active Filters* [1], the following values are given for a 3rd-order butterworth low-pass filter

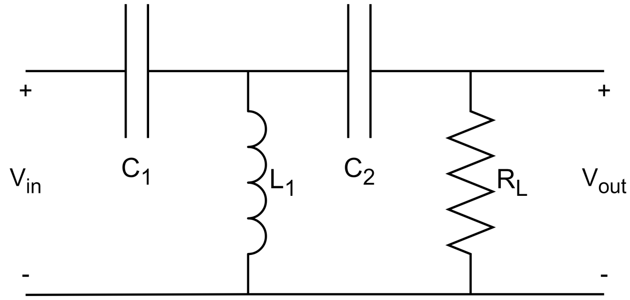

Fig. 1: Passive High-Pass Filter

with a 1 rad/s bandwidth terminated with a resistance of $R = 1\Omega$:

$$\begin{aligned} L_1 &= 1.5000 \\ C_2 &= 1.3334 \\ L_3 &= 0.5000 \end{aligned} \tag{1}$$

To transform the low-pass filter into a high-pass filter, the inductors become capacitors with $C = 1/L$ and the capacitors become inductors with $L = 1/C$. The values for the high-pass filter are thus:

$$\begin{aligned} C_1' &= \frac{1}{L_1} = 0.6667 \\ L_2' &= \frac{1}{C_2} = 0.7500 \\ C_3' &= \frac{1}{L_3} = 2.0000 \end{aligned} \tag{2}$$

To denormalize the filter such that the cutoff frequency is $f_c = 1$ kHz or $\omega_c = 2\pi f_c = 3141.59$ rad/s and with a load resistance of $R_L = 1$ kΩ, the component values should be scaled accordingly:

$$\begin{aligned} C_1'' &= \frac{C_1'}{R\omega_c} = 106.10 \text{ nF} \\ L_2'' &= \frac{RL_2'}{\omega_c} = 119.37 \text{ mH} \\ C_3'' &= \frac{C_3'}{R\omega_c} = 318.31 \text{ nF} \end{aligned} \tag{3}$$

B. Experimental Setup

To explore the difficulties of working with inductors, the single inductor in the design was built with two inductors in series, L_{11} and L_{12}. They were placed orthogonally to each other to minimize the coupling between them as shown in Fig. 4. To keep the circuit compact and simple, the components values were chosen to match the design values as closely as possible, however, given the available components and the coupling between the inductors, the measured values are not identical to the design values. The component values are shown in Table I.

The frequency response of the filter was measured by collecting the input and output voltages at octave intervals from 2 Hz to 20 MHz using the oscilloscope's function generator and probes connected to the input and output. The interval at which the expected cutoff frequency is located was measured with more detail, collecting data at 0.1 kHz intervals from

TABLE I: Component Values

Component	Design	Ideal	Measured
C_1	106.10 nF	100 nF	93.9543 nF
C_2	318.31 nF	330 nF	354.231 nF
L_{11}	NA	68 mH	68.5271 mH
L_{12}	NA	68 mH	68.4791 mH
L_1	119.37 mH	NA	225.395 mH
R_{ind}	0 Ω	NA	104.016 Ω
R_L	1 kΩ	1kΩ	0.99853 kΩ

1 kHz to 2 kHz. At lower frequencies, the output voltage was below what the oscilloscope could measure, however, the oscilloscope's function generator was limited to a max voltage peak-to-peak of 5V, which was not enough to measure the output voltage at low frequencies. As a result, a separate function generator was used which could output a higher voltage but with a smaller range of frequencies.

The roll-off rate was calculated as the maximum derivative of the gain with respect to frequency.

C. Simulation

The circuit was simulated using LTSpice to compare the measured results with the expected behavior of the filter. The simulation was set up to match the experimental measured component values, including the inductor's winding resistance.

III. Results and Discussion

A. Frequency Response

The collected measurements are given in Table II, and the frequency response is plotted in Fig. 2 with the simulated response for comparison. The measured frequency response crosses the -3 dB line at 1.218 kHz, which is only slightly lower than the simulated cutoff frequency of 1.419 kHz. The original frequency response also shows a plateau below 100 Hz which is likely due to the limited accuracy of the oscilloscope at low voltages, which is close to 110 mV at the output in this range. The frequency response from the higher voltage function generator seems to support this hypothesis as it lacks the plateau. Unfortunately, given the limited frequency range of the function generator, the lower frequencies could not be measured and from the plot, and from Table II, the output voltage again hit the supposed minimum voltage of 110 mV at 20 Hz.

From the original function generator there is also an increase in the gain at high frequencies past around 1 MHz where Table II shows that the output does not deviate significantly, instead the input voltage appears to fall off; the cause of this is not clear.

B. Roll-off Rate

For a third-order filter, the expected roll-off rate is $20 \times 3 = 60$ dB / decade, which is consistent with the simulated roll-off rate shown in Fig. 3. However, the measured roll-off rate

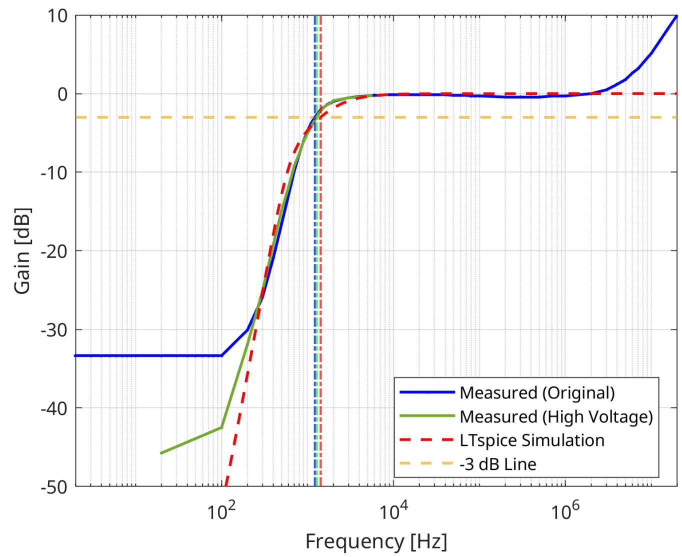

Fig. 2: Frequency Response: the measured responses crosses the -3 dB line at 1.218 kHz, and the simulated response crosses at 1.419 kHz.

was found to be approximately 46.01 dB / decade, which is closer to the expected 40 dB / decade for a second-order filter. This may again be due to the oscilloscope's limited accuracy at low voltages as the measured roll-off rate only begins to increase after 100 Hz, where at which point the simulated roll-off rate is already over 50 dB. However, using a higher voltage function generator did not fully address this issue as the roll-off does improve slightly but still significantly lower than the simulation. The derivative values are given in Table III.

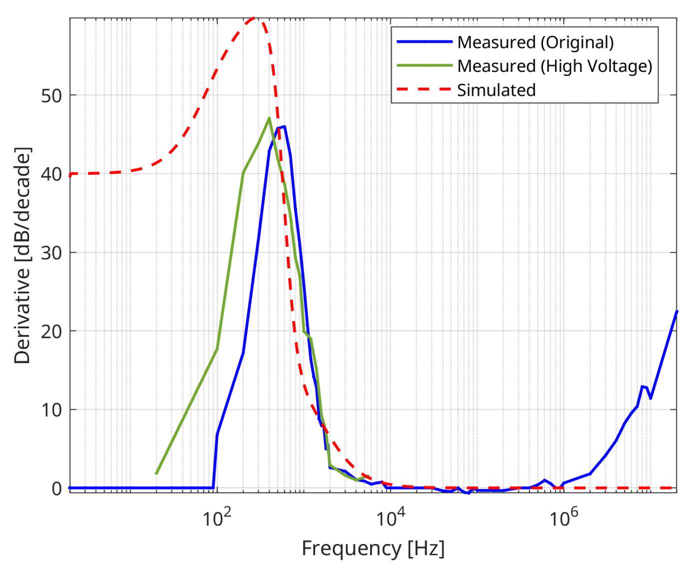

Fig. 3: Derivative of Gain: the roll-off rate is interpreted as the maximum in the stopband; the measured roll-off rate is approximately 46.01 dB/decade, and the simulated roll-off rate is 60 dB/decade.

IV. Appendix

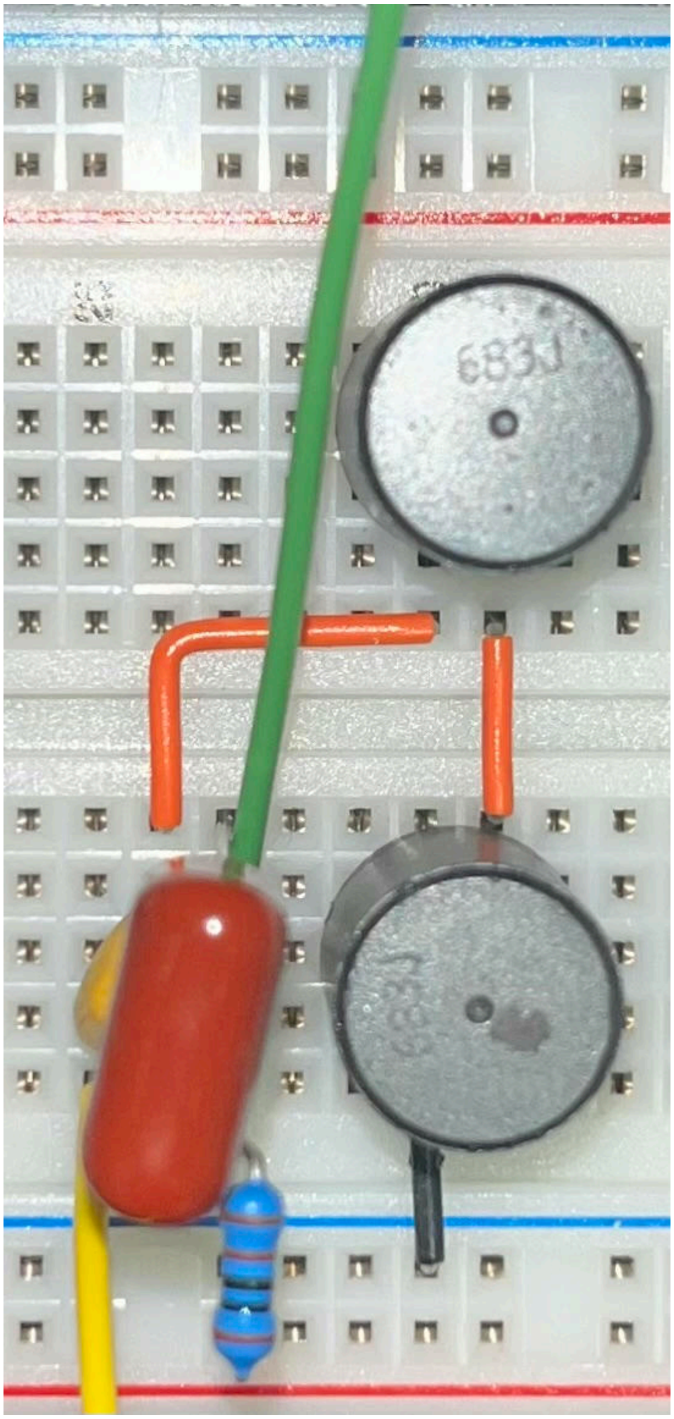

Fig. 4: Experimental Circuit: input at yellow wire, output at green wire. L_{11} is the top inductor with its pins direction facing southeast, L_{12} is the bottom inductor with its pins direction facing southwest.

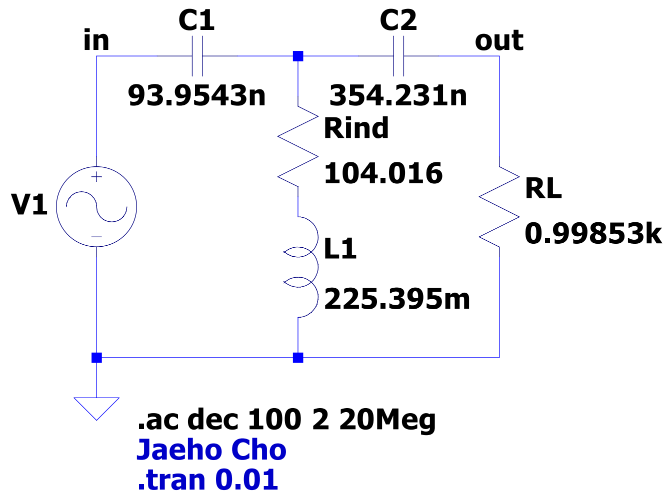

Fig. 5: LTSpice Schematic

TABLE II: Measured Frequency Response Values

f [Hz]	Original V_{in} [V]	Original V_{out} [V]	Original Gain [dB]	High V_{in} [V]	High V_{out} [V]	High Gain [dB]
2	5.11	0.11	-33.34	NaN	NaN	NaN
3	5.11	0.11	-33.34	NaN	NaN	NaN
4	5.11	0.11	-33.34	NaN	NaN	NaN
5	5.11	0.11	-33.34	NaN	NaN	NaN
6	5.11	0.11	-33.34	NaN	NaN	NaN
7	5.11	0.11	-33.34	NaN	NaN	NaN
8	5.11	0.11	-33.34	NaN	NaN	NaN
9	5.11	0.11	-33.34	NaN	NaN	NaN
10	5.11	0.11	-33.34	NaN	NaN	NaN
20	5.11	0.11	-33.34	21.3	0.11	-45.74
30	5.11	0.11	-33.34	21.3	0.12	-45.33
40	5.11	0.11	-33.34	21.3	0.12	-44.93
50	5.11	0.11	-33.34	21.3	0.13	-44.52
60	5.11	0.11	-33.34	21.3	0.14	-44.12
70	5.11	0.11	-33.34	21.3	0.14	-43.71
80	5.11	0.11	-33.34	21.3	0.15	-43.3
90	5.11	0.11	-33.34	21.3	0.15	-42.9
100	5.11	0.11	-33.34	21.3	0.16	-42.49
200	5.11	0.16	-30.09	21.3	0.54	-31.92
300	5.11	0.26	-25.87	21.3	1.19	-25.06
400	5.11	0.46	-20.91	21.3	2.33	-19.22
500	5.11	0.76	-16.55	21.3	3.86	-14.84
600	5.07	1.14	-12.96	21.3	5.39	-11.94
700	5.03	1.61	-9.89	21.1	7.28	-9.24
800	5.03	2.07	-7.71	21.1	8.76	-7.64
900	5.03	2.51	-6.04	21.1	10.5	-6.06
1000	4.98	2.89	-4.73	20.9	11.7	-5.04
1100	4.98	3.22	-3.79	20.8	12.8	-4.25
1200	4.94	3.46	-3.09	20.7	13.9	-3.46
1300	4.94	3.66	-2.6	20.7	14.9	-2.88
1400	4.94	3.86	-2.14	20.7	15.9	-2.29
1500	4.9	3.98	-1.81	20.5	16.4	-1.94
1600	4.9	4.06	-1.63	20.3	16.9	-1.59
1700	4.9	4.18	-1.38	20.3	17.2	-1.44
1800	4.86	4.22	-1.23	20.3	17.5	-1.29
1900	4.86	4.26	-1.14	20.3	17.9	-1.1
2000	4.86	4.34	-0.98	20.3	18.3	-0.9
3000	4.86	4.58	-0.52	20.3	19.1	-0.53
4000	4.86	4.66	-0.37	20.3	19.3	-0.44
5000	4.86	4.7	-0.29	20.3	19.57	-0.32
5500	4.86	4.72	-0.26	20.3	19.7	-0.26
6000	4.86	4.74	-0.22	NaN	NaN	NaN
7000	4.86	4.74	-0.22	NaN	NaN	NaN
8000	4.86	4.78	-0.14	NaN	NaN	NaN
9000	4.86	4.78	-0.14	NaN	NaN	NaN
10000	4.86	4.78	-0.14	NaN	NaN	NaN
20000	4.86	4.78	-0.14	NaN	NaN	NaN
30000	4.86	4.78	-0.14	NaN	NaN	NaN
40000	4.86	4.78	-0.14	NaN	NaN	NaN
50000	4.86	4.74	-0.22	NaN	NaN	NaN
60000	4.86	4.74	-0.22	NaN	NaN	NaN
70000	4.86	4.74	-0.22	NaN	NaN	NaN
80000	4.86	4.7	-0.29	NaN	NaN	NaN
90000	4.86	4.7	-0.29	NaN	NaN	NaN
100000	4.86	4.7	-0.29	NaN	NaN	NaN
200000	4.86	4.62	-0.44	NaN	NaN	NaN
300000	4.86	4.62	-0.44	NaN	NaN	NaN
400000	4.86	4.62	-0.44	NaN	NaN	NaN
500000	4.86	4.62	-0.44	NaN	NaN	NaN
600000	4.82	4.62	-0.37	NaN	NaN	NaN
700000	4.78	4.62	-0.3	NaN	NaN	NaN
800000	4.78	4.62	-0.3	NaN	NaN	NaN
900000	4.78	4.62	-0.3	NaN	NaN	NaN
1000000	4.78	4.62	-0.3	NaN	NaN	NaN
2000000	4.54	4.54	0	NaN	NaN	NaN
3000000	4.22	4.46	0.48	NaN	NaN	NaN
4000000	3.82	4.38	1.19	NaN	NaN	NaN
5000000	3.5	4.3	1.79	NaN	NaN	NaN
6000000	3.18	4.3	2.62	NaN	NaN	NaN
7000000	2.93	4.22	3.17	NaN	NaN	NaN
8000000	2.69	4.22	3.91	NaN	NaN	NaN
9000000	2.5	4.23	4.57	NaN	NaN	NaN
10000000	2.34	4.23	5.14	NaN	NaN	NaN
20000000	1.36	4.31	10.02	NaN	NaN	NaN

TABLE III: Gain Derivative Values

f [Hz]	Original [dB/decade]	High [dB/decade]	Simulated [dB/decade]
2	0	-1.69	39.56
3	0	-1.49	40.03
4	0	-1.29	40.06
5	0	-1.09	40.09
6	0	-0.9	40.13
7	0	-0.7	40.18
8	0	-0.5	40.23
9	0	-0.3	40.3
10	0	-0.11	40.36
20	0	1.87	41.39
30	0	3.85	42.89
40	0	5.82	44.63
50	0	7.8	46.42
60	0	9.77	48.14
70	0	11.75	49.7
80	0	13.73	51.08
90	0	15.7	52.29
100	6.8	17.68	53.35
200	17.2	40.13	58.72
300	31.71	43.86	59.78
400	42.92	47.06	56.51
500	45.76	41.91	47.41
600	46.01	38.68	35.39
700	42.31	34.65	25.46
800	35.46	29.29	19.14
900	30.88	26.94	15.47
1000	25.9	19.96	13.28
1100	20.77	19.48	11.87
1200	16.44	19	10.86
1300	14.22	17.03	10.07
1400	12.73	15.07	9.4
1500	8.81	12.14	8.82
1600	7.92	9.21	8.28
1700	7.83	8.18	7.79
1800	4.97	7.15	7.34
1900	5.47	5.03	6.91
2000	2.6	2.92	6.52
3000	2.11	1.59	3.76
4000	1.06	0.99	2.36
5000	0.86	1.34	1.6
6000	0.48	1.69	1.14
7000	0.64	2.04	0.86
8000	0.74	2.39	0.66
9000	0	2.74	0.53
10000	0	3.09	0.43
20000	0	6.59	0.11
30000	0	10.09	0.05
40000	-0.37	13.59	0.03
50000	-0.46	17.09	0.02
60000	0	20.59	0.01
70000	-0.56	24.09	0.01
80000	-0.64	27.59	0.01
90000	0	31.09	0.01
100000	-0.31	34.59	0
200000	-0.35	69.59	0
300000	0	104.59	0
400000	0	139.59	0
500000	0.4	174.59	0
600000	0.97	209.59	0
700000	0.56	244.59	0
800000	0	279.59	0
900000	0	314.59	0
1000000	0.63	349.59	0
2000000	1.8	699.58	0
3000000	4.11	1049.57	0
4000000	6.03	1399.57	0
5000000	8.23	1749.56	0
6000000	9.53	2099.55	0
7000000	10.4	2449.55	0
8000000	12.89	2799.54	0
9000000	12.74	3149.53	0
10000000	11.41	3499.52	0
20000000	22.47	6999.45	0

References

[1] L. P. Huelsman and P. E. Allen, *Introduction to the Theory and Design of Active Filters*. New York: McGraw-Hill, 1980.