Filter Design Analysis for Phonocardiograms

Team 15

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Introduction

A key issue in denoising and filtering heart sounds in phonocardiograms is managing to extract the correct frequency range whilst altering the heart signal as little as possible. The most clinically significant sounds the heart makes are S1 and S2, which signify valve closure events and are the most useful in diagnosing CVD complications. Sounds S3 and S4 are filling sounds, and while significant at times when diagnosing CVD, their lower amplitude signals can be difficult to measure and thus will not be focused on in this project.

The S1 and S2 sounds may produce frequencies in the range of 10 to 140 Hz and 10 to 400 Hz respectively [1]. However, in constraining the frequency to be most useful, it is also important to consider the normal heart sound signal range, 20 to 200 Hz. So, in designing a PCG, it is necessary to consider the frequencies of possible noise, the possible frequency range of S1 and S2, and the frequency range of the normal heart sound signal. In considering all these factors, we decided to examine low pass filters with a cutoff at 250Hz.

Since we are trying to filter a signal while altering it as little as possible, the ideal case would be to have a filter with a transfer function that looks like a unit step down at 250 Hz. Due to practical limitations this is not possible utilizing analog circuit design techniques, but different filtering techniques can approximate this ideal filter to varying degrees of success.

The Butterworth filter is a promising filtering method that allows for the included frequency range to have minimal distortion, due to being maximally flat in the passband region. The filter still struggles from a non-ideal transition from the passband to the stopband, but this can be improved with higher order filters if necessary.

The Chebyshev filter is another promising filtering method, noteworthy for its comparatively steeper roll-off in the transition region. However, this comes with greater ripple in the passband or stop band depending on the type (type I Chebyshev has greater ripple in the passband, type II or inverse Chebyshev has greater ripple in the stopband).

There are tradeoffs when considering different filters. Thus, we wish to further examine these tradeoffs and how they affect heart sound signals. For reference, a rough depiction of each filter frequency response is depicted in Figure 1.

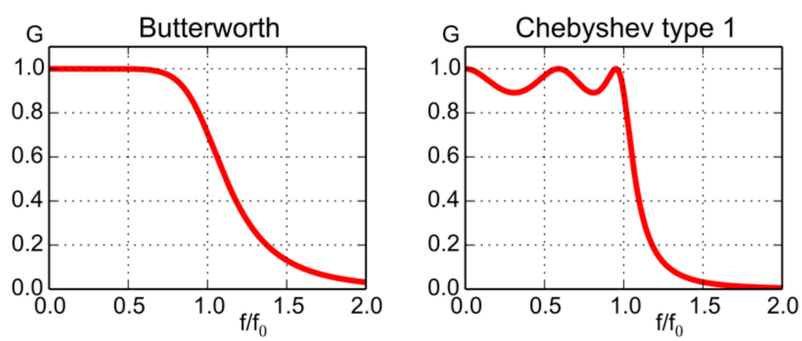

Figure 1 Frequency response curves of 5th order Butterworth and Chebyshev filters [2]

Methods and Materials

For circuit design, we used a backward + forward propagation approach, in which we first define desired circuit behavior, then define component parameters as simply as possible to adhere to the desired behavior. This refers to the 'backward propagation' mechanism. Next, we note that these 'ideal' circuit components may not be obtainable and use E95 standard components to find the closest component matches for our desired components to obtain the manufacturable design. This step refers to the 'forward propagation' mechanism. At this point, the circuit will be realizable and have near desired behavior. We then simulate the realizable circuits and compare them to our theoretical model as a means of checking.

In designing the two filters, Sallen-Key topology was used with the addition of two resistors for setting gain as shown in Figure 2. Note that both filters analyzed in our experiment, the Butterworth and Chebyshev filters, utilize the same Sallen-Key topology, and thus have the same transfer functions. The difference between the filters fundamentally arises from differences in component values, and how they affect the coefficients of the transfer function.

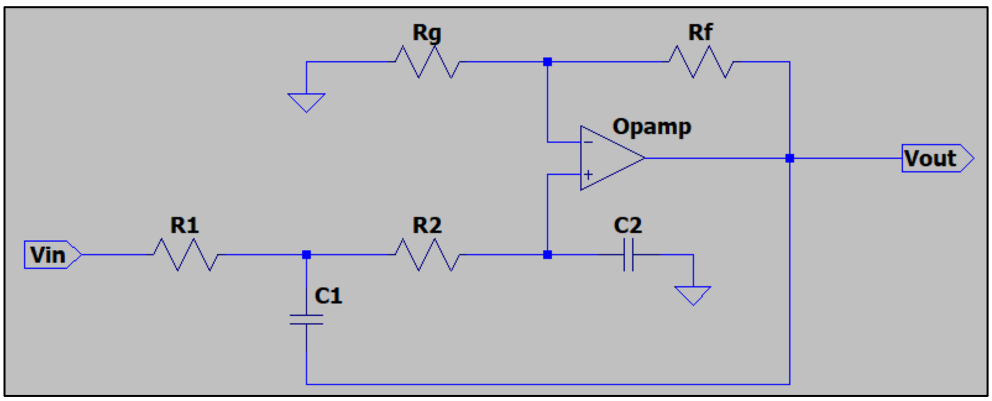

Figure 2: Sallen-Key circuit topology

The general frequency response formula for the Sallen-Key filter topology used is listed below in Equation 1.

$$H(s) = \frac{K\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0}$$

Equation 1: General Frequency Response of Sallen-Key Filter

K is the closed-loop gain where $K = 1 + \frac{R_f}{R_g}$, Q is the quality factor where $Q = \frac{1}{3-K}$ and describes how damped the system is, and ω_0 is the natural frequency where $\omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$. As a simplification, we have set $R = R_1 = R_2$ and $C = C_1 = C_2$, making $\omega_0 = \frac{1}{RC}$

In designing a Butterworth filter, achieving maximal flatness requires the quality factor to be $Q = \frac{1}{\sqrt{2}}$, meaning $K = 3 - \sqrt{2} \approx 1.586$ and $\frac{R_f}{R_g} \approx 0.586$. Using E95 standard components, we set $R_f = 37.4k\Omega$ and $R_g = 63.4k\Omega$ to achieve a value close to 0.586. From here, we set the natural frequency to the cutoff frequency we are after, so to get $250Hz$ we set $C = 10nF$ and $R = 63.4k\Omega$ since $\frac{1}{63.4k\Omega \cdot 10nF} \approx 1577.29\frac{rad}{sec} \approx 251.03Hz$.

In designing a Chebyshev filter, the same R and C values used in the Butterworth filter are used here, since we are trying to achieve the same cutoff frequency for both. In designing the Chebyshev filter, the gain selection determines the characteristics of the ripple. For our Chebyshev filter, we chose to have a maximum ripple of 1dB which requires a Q value of 0.957, which needs a K value of 1.961 [4], resulting in us choosing values $R_f = 60.9k\Omega$ and $R_g = 63.4k\Omega$ to achieve a close 1dB ripple characteristic while still using E95 standard components.

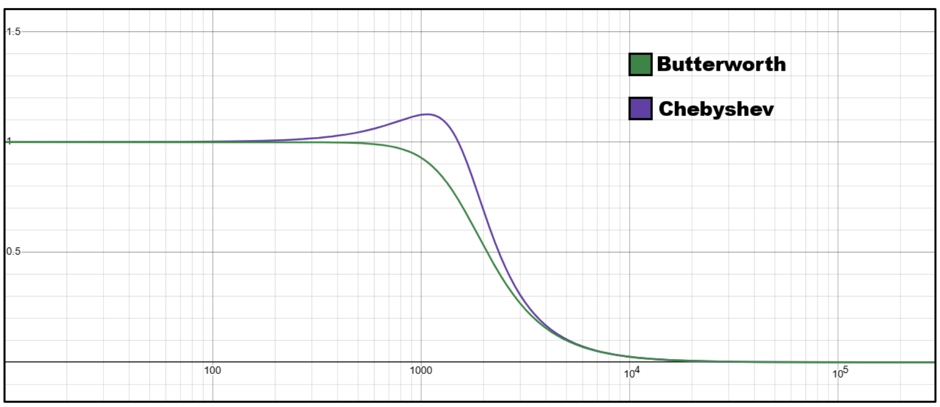

Figure 3: Butterworth and Chebyshev filter magnitude responses, normalized

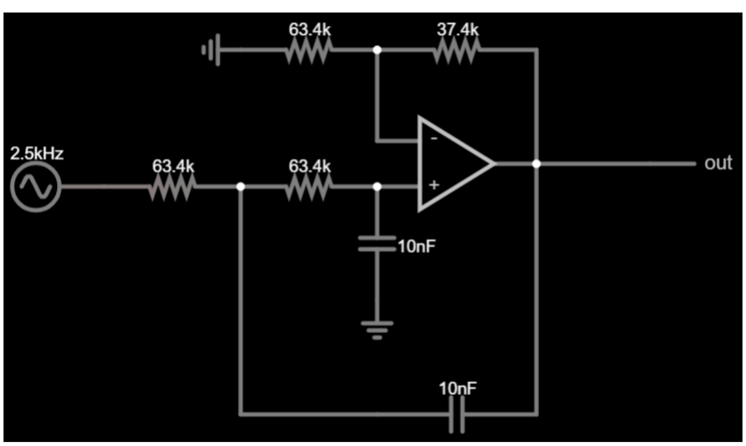

Figure 4: Butterworth filter circuit

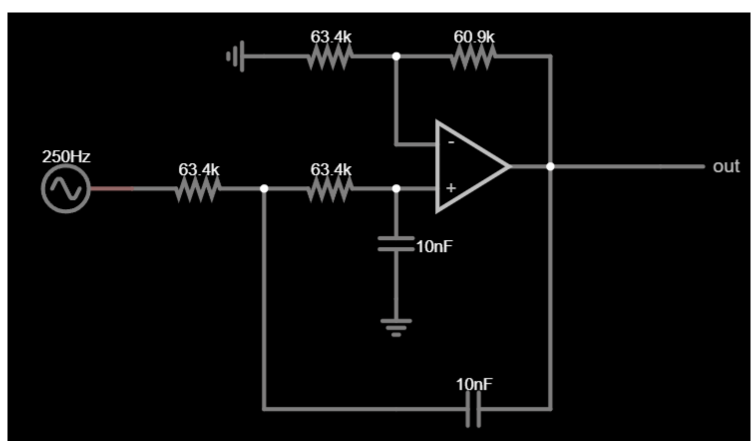

Figure 5: Chebyshev filter circuit

Results and Discussion

Using Falstad, we built both filters, as seen in figures 4 and 5, and tested multiple frequencies and compared them to our predicted frequency response equations. For simulating, we input a 1V AC signal at various frequencies from 25Hz to 10kHz, the results of which can be viewed in tables 1 and 2 where they are compared to their calculated results from Figure 3.

Frequency	25Hz	100Hz	250Hz	1kHz	2.5kHz	10kHz
Butterworth Calculated	1.590V	1.572V	1.132V	0.100V	0.0160V	0.00100V
Butterworth Simulated	1.616V	1.605V	1.171V	0.101V	0.0163V	0.00100V

Table 1: Butterworth filter calculated and simulated responses

Frequency	25Hz	100Hz	250Hz	1kHz	2.5kHz	10kHz
Chebyshev Calculated	1.969V	2.0909V	1.894V	0.127V	0.0199V	0.00124V
Chebyshev Simulated	1.969V	2.091V	1.893V	0.127V	0.0198V	0.00121V

Table 2: Chebyshev filter calculated and simulated responses

Due to each filter having unique gain factors, the baseline for the Butterworth and Chebyshev passbands should be 1.590 and 1.961, respectively. Meaning that ideally, each filter should output such baseline voltage until 250Hz is reached and then output 0V from 250Hz and on.

These filters are not mathematically ideal, but the simulated values are reliably close to their calculated values, indicating that the two graphs in Figure 3 are reliable metrics for understanding each filter's frequency response.

Conclusion

The results indicate that our designed circuits are functional as low pass filters and that our design should work if implemented as hardware, with variations depending on components used and other non-idealities. The differing filter designs, Butterworth and Chebyshev, have managed to illustrate the design tradeoffs that come when implementing analog filters. Particularly, it illustrates the tradeoff between a steep transition band which is better at emulating the transition of a unit step from 1 to 0, and a stable passband which allows for data to be filtered without significant alteration.

For the phonocardiogram, this brings a relevant concern: does signal integrity of passband signals matter more than the transition bandwidth. Due to the nature of the signals, we used the 250 Hz cutoff as a rough range. That is, stopband frequencies above 250 Hz are not necessarily improper data points to utilize; they are simply the ones designed to be attenuated by the circuit. Functionally, this means that the Butterworth filter can safely and stably harvest all the data in the passband, as well as the higher frequences, albeit with droop in their magnitudes. In contrast, the Chebyshev better attenuates these higher, but still safe, frequencies at the cost of muddling the passband data. Since passband data is what the filter is designed to safely extract for monitoring, it seems like a poor choice for this medical application to utilize this design. The findings from literature align with our independent conclusion that the Butterworth filter is better suited for this application than the Chebyshev filters [1]. Additionally, the magnitude differences between passband and stopband frequencies can be further stabilized to digital values as needed through a sense amplifier or ADC circuit.

References

[1] R. M. Potdar, M. R. Meshram, and R. Kumar, “Design and analysis of a PCG acquisition and denoising circuit,” *Turkish Journal of Physiotherapy and Rehabilitation*, vol. 32, no. 3, pp. 750–764, May 2021. [Online]. Available: https://www.researchgate.net/publication/351879628_Design_and_Analysis_of_a_PCG_Acquisition_and_Denoising_Circuit

[2] L. Balestra and I. Schjølberg, “Hybrid powerplant configuration model for marine vessel equipped with hydrogen fuel-cells,” *preprint*, Oct. 2022. [Online]. Available: https://www.researchgate.net/publication/364707623_Hybrid_powerplant_configuration_model_for_marine_vessel_equipped_with_hydrogen_fuel-cells

[3] “Second Order Low Pass Butterworth Filter | Transfer Function,” *EEEGUIDE.COM*, Sep. 08, 2016. https://www.eeeguide.com/second-order-low-pass-butterworth-filter/
[4] “Chebyshev Filters,” *StudFiles*, 2023. https://studfile.net/preview/17110350/page:37/ (accessed May 04, 2026).