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BMS3676: Principles of Medical Engineering

Project B

Circuit Specification of the Electrocardiogram

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Abstract

The application of anti-alias filter is a necessity in the design of ADC conversion. Failing to do so the fidelity of signal may be loss, which can cause misreading that can have terrible consequences, especially in medical equipment's. On this project we are going to study and simulate a 3 order Butterworth Low pass Filter in ECG application and create designs for a virtual bread board and PCB layout in *multisim* to obtain results for the passband and verify if they correspond with the requests indicated in the ISO. We will then compare the results from the simulation with the analytical expression and study how the worst case can have a large impact on the predicted attenuation and phase. This project represents an attempt to understand the necessity of analog anti-alias filter in the ECG and to use the tools of *multisim* that proved to be very suitable for this analysis.

1. Introduction

The electrocardiogram (ECG) is a commonly used medical device that is capable to measure the heart electrical conductivity. The circuit design of an ECG is composed by electrodes that are attached to the body of a patient, that are able to capture and transduce the action potential of the heart into small voltage signals that then can be latter graphed. The principal component in the ECG equipment is the amplifier, that takes up these inputs signals and increases them to a higher signal voltage allowing them to become measurable. However, due to the susceptibility of amplifiers to various noises sources, it is important for its components to be properly isolated and use short cables. It also requires the use of filters to limit the bandwidth and remove unnecessary frequencies that can cause interference that can lead to aliasing or be harmful to the patient. Finally, the signal needs to be sampled and converted to digital format in order to be processed to an output that can illustrate the cardiac electrical potential. The ECG is not a direct measurement of the mechanics properties of the heart and therefore does not allow the reading of blood pressure or the strength of myocardial contractibility. However, for each deformation in the graph of the ECG it corresponds to an electrical event in the heart that subsequently illustrates consequences in the mechanical properties. By this means the ECG is a method of diagnosis extremely valuable for the identification of numerous cardiac anomalies without intervention and invasiveness. Abnormal heart rhythms, hypertrophy of some heart parts or the localization of damaging areas in the heart muscle are some example of problems that can be detected by the ECG (Seeley, Stephens and Tate, 2003).

The heart works by being initially polarized at rest with the excess of sodium ions (Na+) outside the membrane. This correlates to a resting potential of approximal 90 mV. When muscle simulation occurs, the permeability of this membrane increases leading to the entry of more sodium and other ions. This causes an alteration in the electrical field around the muscular cells, generating action potential and causing muscle contraction. The other ions involved in the process are potassium, calcium, and chlorine. In the ECG graph the deflection in the ECG waveforms correspond to the contraction of different areas in the heart. Each heart cycle is composed by a P wave, a QRS complex, and a T wave. The P wave is the result of the depolarization of the atria. The QRS complex is composed by three waves: Q wave, R wave and S wave. The origin of the QRS complex is the depolarization of the ventricles. The T wave represents the repolarization of the ventricles and precedes the relaxation of the ventricles. The reason why there is no visible waveform for the repolarization of the atria is because this wave occurs at the same time as the QRS complex. During the QRS complex, the period of time between the P wave and the beginning of the QRS complex is an interval known by PR due to the short-wave Q. During the interval PR, that lasts at least 0.16 seconds, the atria contracts and starts relaxing and the ventricles to depolarize at the end of the PR interval. The QT interval extends until the end of wave T, lasting approximately 0.36 seconds and represents the necessary duration for the ventriculus to contract and relax (Jakoi 2015).

In this report we are going to design a third order Butterworth filter for anti-aliasing in an ECG recorder that samples at 1000 times a second. For this it will be necessary the use of a Low pass filter (LPF) to cut all the possible frequencies that may cause aliasing and offer minimum attenuation in the expected typical pass band for ECG recording. This will be accomplished by virtually simulate the circuit schematic, prototype the layout on a virtual bread board and design a single-sided PCB layout using the software *multisim*.

1.1. Engineering basis for the circuit

To create the circuit design for the anti-alias low pass filter (LPF) of the ECG, it required us to follow the International Organization for Standardization (ISO) to find out the requisites necessary for the specifications of the frequencies for the passband, stopband, and sampling.

An anti-aliasing filter is an analog mechanism, used after the analog-input and before sampling, that is responsible for filtering out undesirable high frequency components and restricting the bandwidth before being converted to the digital output. The ideal anti-alias is a low pass filter that perfectly rejects all frequencies above the Nyquist-Shannon sampling theorem, preventing aliasing over the band of interest. Unfortunately, such filter is unrealizable and real anti-alias filter does not have immediate rejection of the signals in the stop band having a transition region between pass band and stop band. At the moment one of the best types of LPF for the ECG is the Butterworth filter that can have a sufficient high attenuation in the transition region and does not imposes risk of disrupting the signal. According to an International standard recommendation, the bandwidth frequency range for an adult ECG should go up to at least 500 Hz in order to reproduce all measurable high-frequency components and minimise the error, this allowable range is between 0.025 mV to 0.050 mV based on human visual ability. Finally, in relevance to this project, it is claimed that minimum sampling rate can be of 500 as long this has a maximum 1% error waveform (Bailey *et al* 1990).

Sampling is a core aspect of analog to digital conversion. When designing a filter or any other electrical system that requires conversion of analog to digital engineers must consider the minimum sampling rate allowed for the sampling to accurately recreate the continuous signal. Failing to do so, serious problems can arise in the circuit and lead to aliasing. A signal is a composition of encoding information by using variation in the frequency's bands. When a signal is converted from analog to a digital, a continuous signal is converted to a discrete one by sampling. In other words, the capture of the analog pulses signal is digitalized and so when a high frequency is digitized with a low interval samples, issues in the signal processing arises in the image synthesis because of the transformation between continuous and the discrete representation. This issue is called Aliasing and refers to the failure to reconstruct the original signal, causing it to appear as a completely different wave of a lower frequency (Mitchell and Netravali 1988).

To combat this problem, we use the Nyquist-Shannon sampling theorem, which tells us the amount of sample rate that should be used for completely recover a continuous-time frequency and prevent aliasing from occurring. The theorem simply states that a sampling rate should be at least double the maximum frequency, more precisely.

$$Sampling\ rate = 2f \tag{1}$$

So we must be careful with sampling and not let the maximum frequency go near the sampling rate as this would only give a fair representation of the signal or in extreme case,

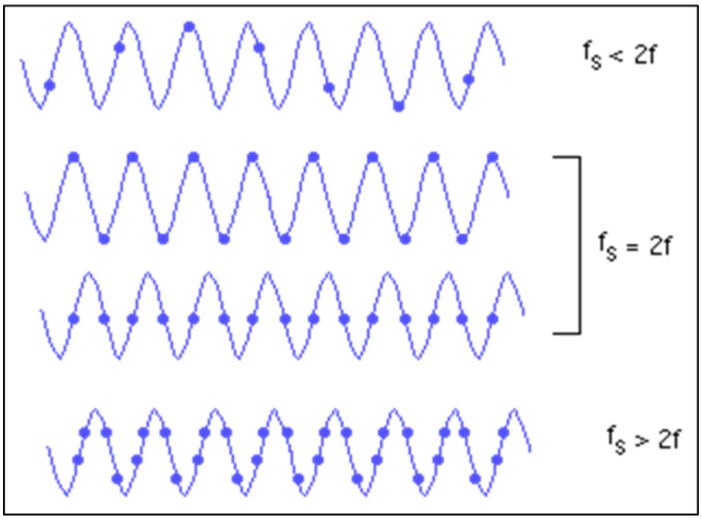

Figure 1: Nyquist theorem
(www.dgp.toronto.edu)

for sinusoidal waves if the frequencies match (*Max f = 2f),* may produce a complete silence signal. So, it is important to salient that for any given sample rate of 2f we can only recover the frequencies less than *f*, and not suffer alias. (Figure 1)

By using this theorem and knowing that the maximum frequency must go until 500 Hz to maintain the fidelity of the high frequency components, the sampling rate chosen for this ECG equipment must be of at least 1000 sample rate, maintaining this way the ISO fidelity criterion and RMS error criteria described (Bailey *et al* 1990). For the bandwidth there is no specification for the performance of the analog LPF. However, according to the American National Standard Association for the Advancement of Medical Instrumentation (AAMI) EC1110 and the International Standard IEC 60601-2-51, is requested to keep the output amplitude within the range +10% to -100% of true amplitude when varying the input signal frequency from 150 to 500 Hz (Luo and Johnston 2010).

To follow these recommendations the most appropriate filter for this ECG application is the Butterworth Low Pass Filter. This filter is an analog filter commonly used in anti-aliasing filter to data conversion application, due to its properties of maximum flatness in the passband and stopband and the considerable roll-off after in the cut-off frequency (*fc*) in the transition area (between pass band and stop band), which can be improved by increasing the order. However, this filter is also known by tendency for overshooting, the ripple effect and the non-linear phase response which worsen according to a higher order. In this project the filter simulated was a 3 order Butterworth LPF, which is characterized by its attenuation of 60 dB per decade. Its transfer function for equal resistors and capacitors, that defines the output voltage to input voltage ratio in magnitude and phase (*jw*) domain is:

$$|H(jw)| = \frac{1}{\sqrt{1+\left(\frac{W}{Wc}\right)^{6}}} \qquad (2)$$

The cut-off frequency (*fc*) is point where the attenuation of the filter starts rapidly increasing between the passband and stopband. This is the point of the region which the output voltage drops below 70.7% of its input voltage and corresponds to the frequency at which the magnitude response is 3 dB lower than the original at 0 Hz. To find out the cut-off frequency we either find the expression from the transfer or determining it using a bode plot. For equal resistors and capacitors the equation used to find the cut-off frequency was:

$$fc = \frac{1}{2\,\pi\,R\,C} \qquad (3)$$

2. Methods

We developed 3 virtual designs of the 3^{rd} Butterworth filter to examine the frequencies response to the magnitude and phase, and other the electrical properties. The first design made was of the circuit schematic, which we use to analyse the AC sweep and recall data. While here, also we also made the worst-case analysis to then compare it to the results of the transfer functions. The other design made was of the prototype layout in a virtual bread board environment, which serve us to better understand how the connections were made. Which finally contributed for construction of last design the PC Board layout

2.1. Circuit Schematic

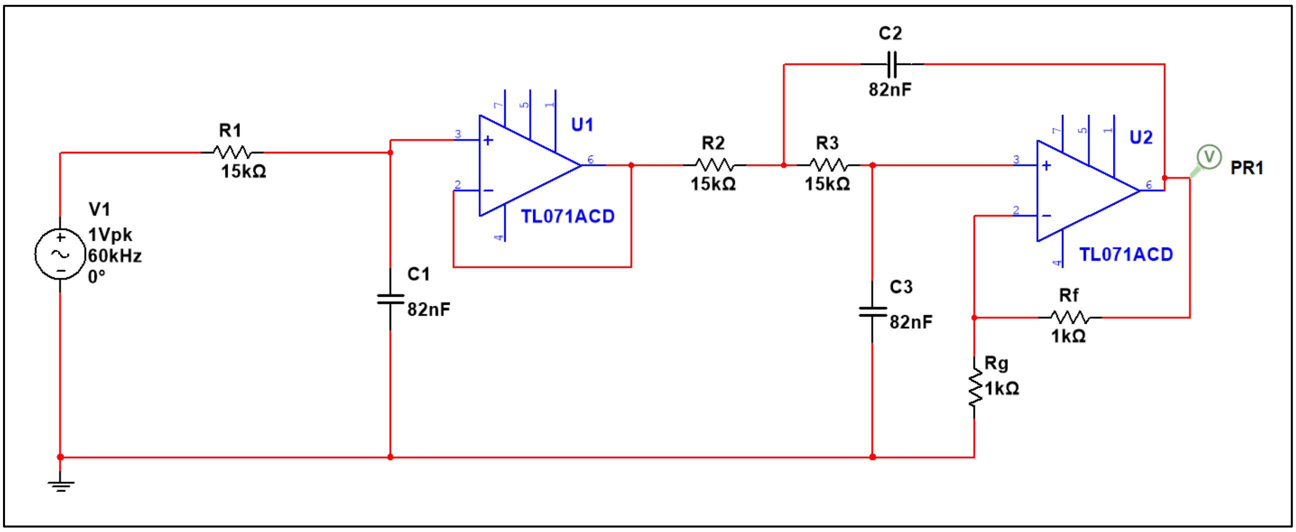

Figure 2: Circuit Schematic of a 3^{rd} Butterworth Low Pass Filter

On the Circuit Schematic of the 3^{rd} Butterworth LPF (Figure 2) the parameters that characterized the input is a 60 kHz, 1 volt AC signal. For the resistors, we assigned a value based on the *fc* formula (3) for the limiting the gain between +10% to -100% when varying from 150 to 500 Hz. This resulted in 15 kΩ, for the exception of the gain resistors (Rf and Rg), which given the necessity to keep the gain ratio to one, the same value was tributed of 1 kΩ. The capacitors, we choose the fixed value of 82 nF. At last to amplify the signal, we used two TL07ACD Low noise JFET Operation Amplifiers that are suited for high-fidelity applications. To evaluate the output we used a Probe at the right-hand side of the second amplifier (PR1) for analysing the voltage and composing the bode plot diagram using the tools in Simulate tab, Analyses and Simulation, AC Sweep.

2.2. Prototype Layout on virtual bread board

To prototype this circuit on a virtual bread board (Figure 4), we used the NI ELVIS II Series design template on *multisim.* This enables us to construct the circuit schematic in a virtual bread board page template and then to export these components to a 3D environment where we can then work out the connections. This can be a good practice tool to check on errors in the circuit and establishing a clear idea of how these connections are made in reality.

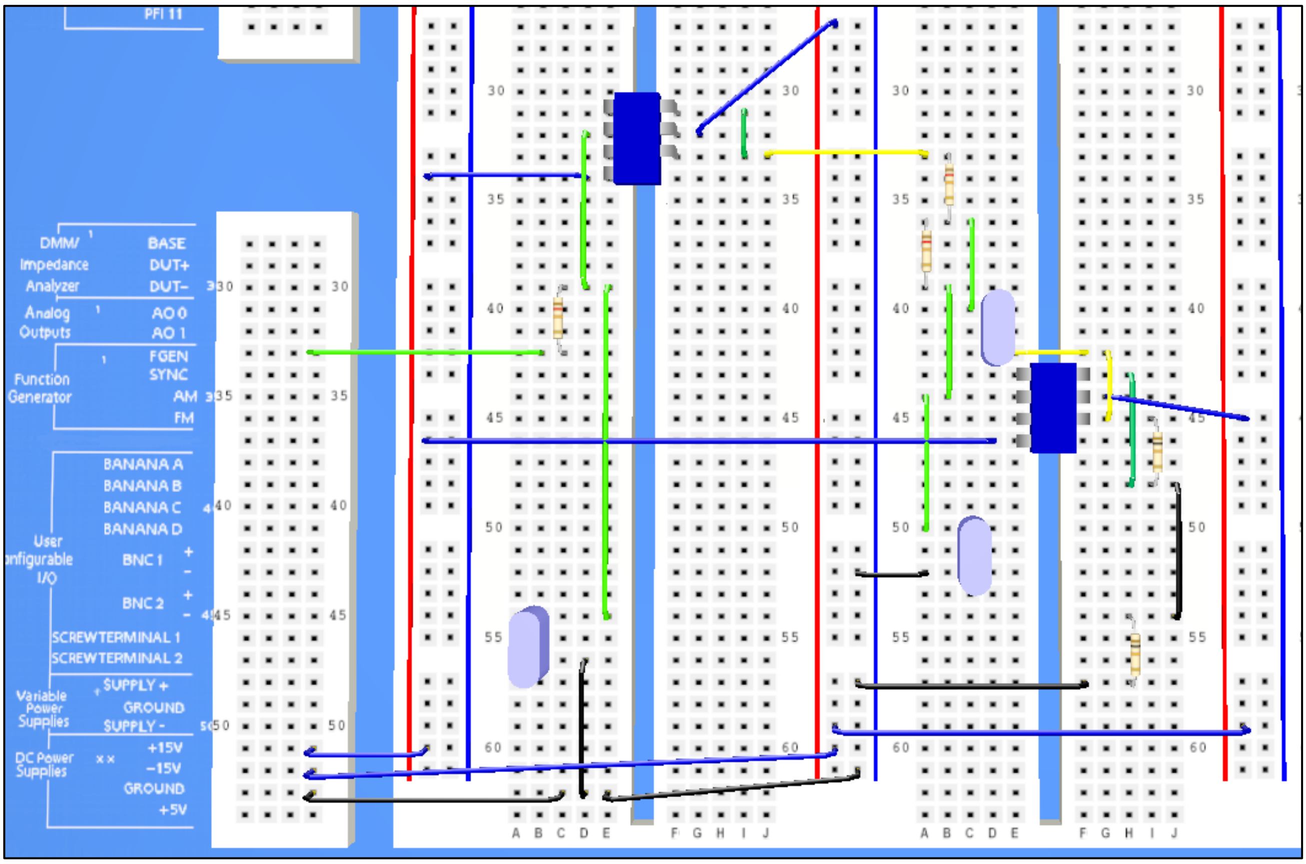

Figure 3: Virtual Bread Prototype of the Butterworth Low Pass Filter

3. Results

We compared the results obtained from the AC Sweep of the 3^{rd} Butterworth Simulation to the analytical approach of the formulas (2) and (3). Figure 5 shows the bode plot generated by this analog anti-alias LPF for the frequency response of the magnitude and phase frequency. As well as the bandwidth generated between of 150 Hz to 500 Hz.

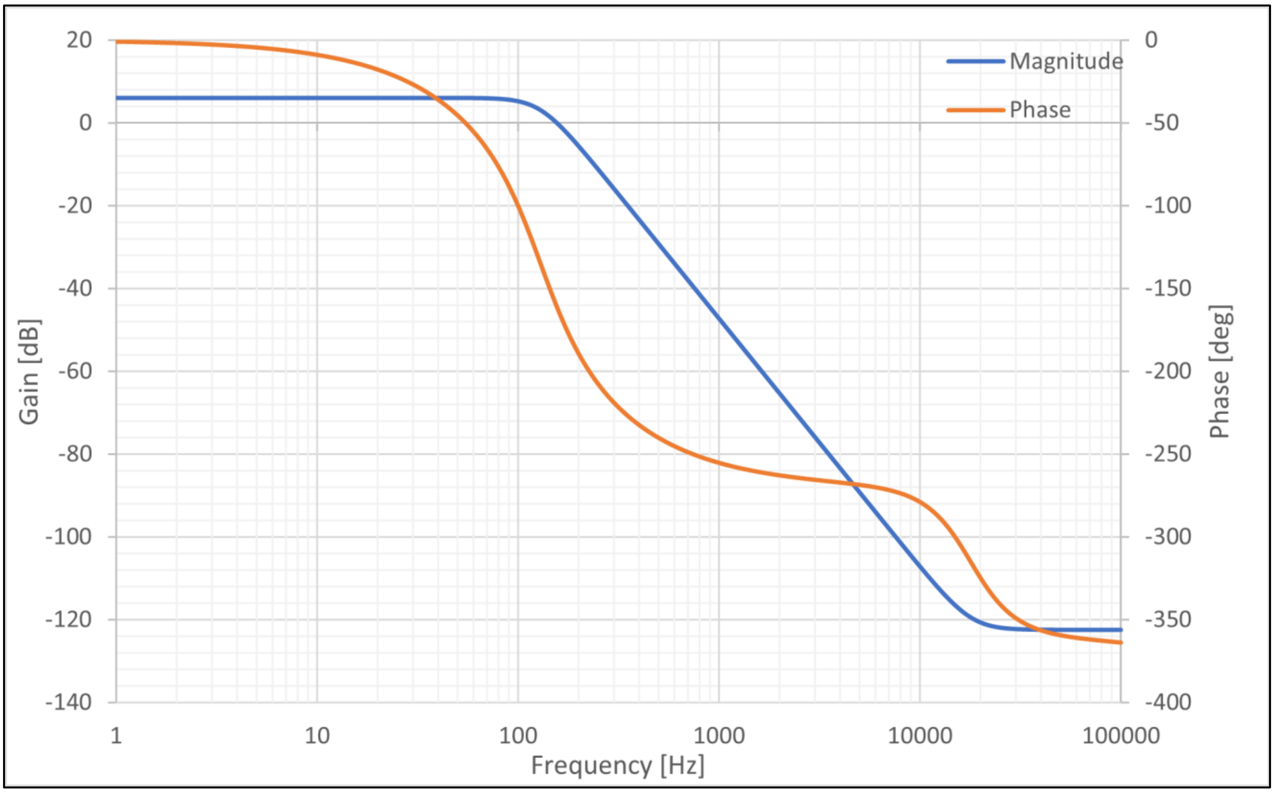

Figure 4: Magnitude and phase of the 3^{rd} Butterworth Low Pass Filter

We notice that for the cut off frequency (*fc*) the frequency response occurs around of 180 Hz and that the Magnitude response at 500 Hz the gain reduced about 29 dB equivalent to 3.5% of the original input. For the for 150 Hz the signal gain had an increase of 0.712 dB which corresponds to 8.8% from the original.-162% for the cut-off frequency and 160.51% for the magnitude response

The data from this simulation represents the nominal case, where every condition is ideal, and this can be verified by the results from the theoretical approach, where the magnitude response at 500 Hz was equal to 0.0347 (3.5%) or -29.2 dB. The ratio between the theorical and the analytical is 72% for the cut-off frequency and 99.67% for the magnitude. This is a good result, given the differences between analytical and simulation. Analytical results are always accurate as they arise from proven mathematical manipulation and the simulation may not always be due to the procedure which the results are based, such as errors in the development of the circuit. So, we should always compare these two results to find out if there is a huge discrepancy between them and find what needs to be modified to minimize errors.

In real events larger deviation always occur between the reality and the analytical. This due to many factors but one of the most common is due to the components that always have tolerance sensitivity from the supposed value. This risks a miscalculation in the predicted cut-off frequency, magnitude and phase response of the filter and may cause an alteration in the gain resistors, which can have a negative impact in the Q-factor and cause a resonance peak in the flat passband or consequently in the bandwidth, and cause aliasing. To prevent this from happening and correctly estimate the risk involved with the component's tolerances, *multisim* gives an option to study the Worst-case analysis which consists of plotting the circuit design using tolerances to the components, and this way ensuring a higher confidence to detect a potential defect in the filter. For the implementation of this analyse, the tolerance sensitivity used in the resistors was 5% and for the capacitors 10% where *multisim* then automatically assigns a new value to them. These values can be seen in Appendix A and the bode plot of the worst-case analysis in figure 5.

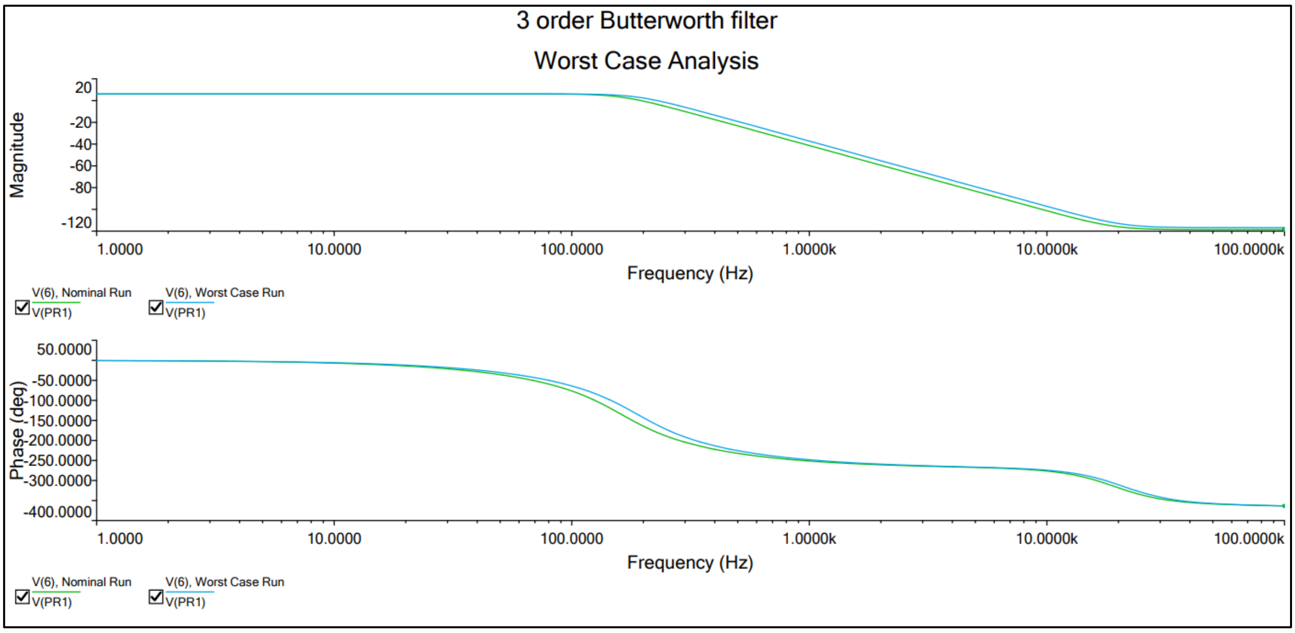

Figure 5: Worst case analysis from multisim

During this examination of the Worst-case analysis, the magnitude of the transfer-function represented by the top graph (figure 5) showed significant difference between the previous simulated circuit, with no tolerances. The results of this worst-case analysis with the change in components tolerances, changed the cut-off frequency response to 210 Hz and the magnitude response at 500 Hz to an attenuation of 25 dB or about 5% of the input. Finally, for the 150 Hz there was in increase in the gain of 3.18 dB or 44% of input. In addition, the ratio between the theorical and the analytical for the worst case is 162% for the cut-off frequency and 160.51% for the magnitude response at 500 Hz. These results show that minor changes of 5% and 10% in the resistors and capacitors in this filter circuit schematic can have substantial effects within the band limit for the attenuation and phase of the LPF.

3.1. Single sided PCB layout

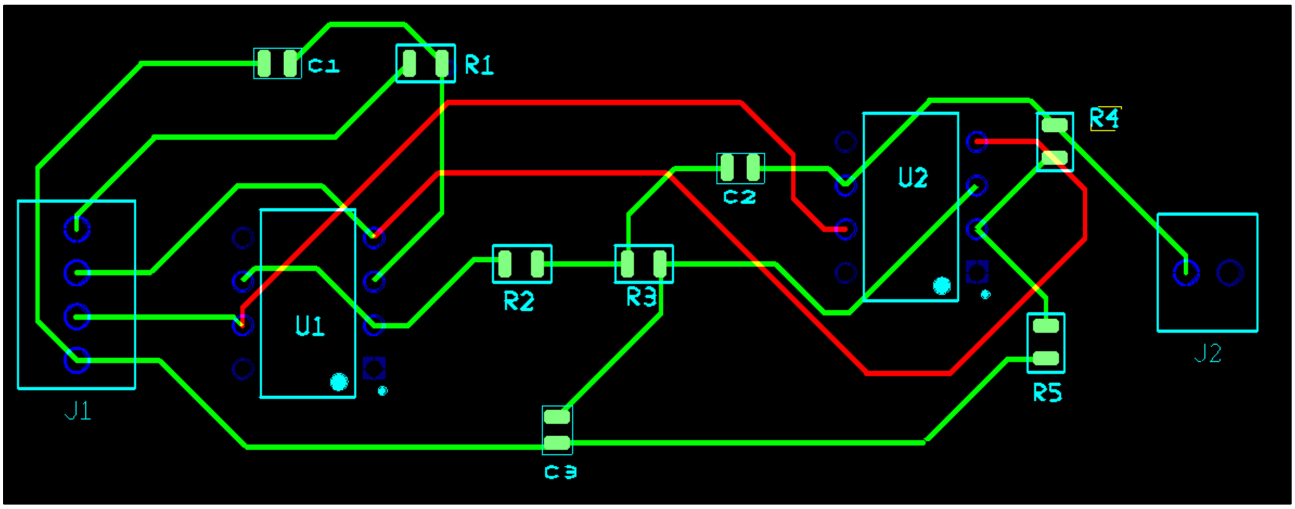

Figure 3: Shows as the result of the layout made for this circuit in a PC board

PCB layout is also an important part that requires attention, for instance if an input-referred noise distribution is found to have large and distinct peaks and valleys, this indicates either a poorly designed ADC or, more likely, a bad PC board layout, with poor grounding techniques, or improper power supply decoupling (Kester, 2005).

4. Discussion and Conclusions

The application of the 3^{rd} Butterworth Low pass filter proved to be an effective anti-alias filter for an ECG application, minimizing the output gain of the frequencies that would cause aliasing and avoiding errors in the translation from analog to digital due to its flat-band properties. However, even due it this LPF contains quick roll-off in the transition region to stop band, the magnitude attenuation at 500 Hz resulted in a 29 dB or 3.5% of the original input (Figure 5) and in a worst-case environment in a 25 dB attenuation about 5.5% of the input (Figure 6). This magnitude response given by the first simulation showed very approximated results in comparison with the analytical approach, based on the transfer-function of equal resistors and capacitors equation (2) and a confidence discharge of

99.90%. Which confirms that agrees with the ISO measures, that for this ECG application the target range was between +10% to -100% of input gain from the 150Hz to 500Hz.

This, simulation suggested that, in accordance with the Nyquist theorem, if the minimum sample rate of 1000 were used for sampling in the worst-case scenario there would be still no significant aliasing, since the attenuation at the stopband is between the required range for a signal to not become alias of 20 to 120 dB (Definition: stopband, 1996). However, for the suppression of noise and interferences, the gain produced by the worst case at the frequency of 150Hz surpass the +10% from the standards. To improve this our recommendation is the use a high-pass filter (notch filter) to filter out these unnecessary low frequencies that could potentially ruin the high-fidelity signal or in danger the patient. We also recommend the of use of high-quality components and the proper routing and ground connections in the PC board layout (figure 6) as this are crucial factors to keep the noise distortions down and maintain the fidelity of the ECG waveforms.

Although the majority of the unwanted hight frequencies was filter by this anti-alias 3^{rd} Butterworth LP filter. There are still limitations in this type of filter, such as the insufficient roll-off in the magnitude response. This problem could be addressed with the increase of the order and the addition of more components. However, this would affect the non-linear phase causing delays at different frequencies regions and worsens the ripple effect. As a result distortions in the ECG waveform would occur such at the PR segment, making impossible to diagnose some heart conditions from being detected (Luo and Johnston 2010). So additional research needs to be made in analog low pass filters to create a filter that offers magnitude attenuation as close to the idealized brick wall and, if possible, to offer a linear-phase response in the passband and transition band.

Our goal with this project was to design a 3^{rd} Butterworth filter for anti-aliasing application in the ECG and provide a simplified estimation for the values of the resistors and capacitors needed to achieve minimum attenuation in the expected passband for ECG recording. This was done by deriving the corner frequency (*fc*) directly from the Butterworth transfer-function and confirming it using a bode plot analyse from the two simulations in *multisim*. We confirm the validity of simulation by comparing the results from the simulation to empirical analytical expression which the results showed to really approximated. Although this anti-alias filter design had several limitations as discussed nonetheless, it proved to be suitable for this kind of filtering due to its nature of few components, the maximal flat passband and decent roll-off.

In conclusion, the analyse of analog to digital anti-alias Low pass filter is important due to the convenient properties that provide a stable passband, the restriction of the high frequencies from aliasing with sampling and the capacity to minimise nonlinear-phase response. Nowadays, thanks to computational simulation tools such as *multisim,* is possible to study and test more circuits in a faster pace, allowing us to step up the research and develop better suitable optimise filters.

5. References

Bailey J J, Berson A S, Garson A, Horan L G, Macfarlane P W, Mortara D W and Zywietz C 1990 Recommendations for standardization and specifications in automated electrocardiography: Bandwidth and digital signal processing. A report for health professionals by an ad hoc Writing Group of the Committee on electrocardiography and Cardiac Electrophysiology of the Council on Clinical Cardiology, American Heart Association Circulation 81 730–9 Online: http://ahajournals.org

Its.bldrdoc.gov. 1996 Definition: stopband. Online: https://www.its.bldrdoc.gov/fs-1037/dir-035/_5133.htm

Jakoi E Introductory Human Physiology CV 1. HEART ELECTRICAL ACTIVTY LEARNING OBJECTIVES

Kester, Walt. (2005). The Good, the Bad, and the Ugly Aspects of ADC Input Noise—Is No Noise Good Noise? MT-004. Analog Devices p.2

Luo S and Johnston P 2010 A review of electrocardiogram filtering Journal of Electrocardiology vol 43 (J Electrocardiol) pp 486–96 Online: https://pubmed.ncbi.nlm.nih.gov/20851409/

Mitchell D P and Netravali A N 1988 Reconstruction filters in computer graphics Computer. Graph. 22 221–8 Online: https://dl.acm.org/doi/10.1145/378456.378514

Seeley, R., Stephens, T. and Tate, P., 2003. Anatomy and Physiology. 6th ed. McGraw-Hill Science Engineering, pp.693-707

Appendix A:

Table 1: Data from the tolerances changes for the worst-case analysis simulations

Worst Case Run
AC analysis for all devices: 2.00032e-07 higher at frequency = 40.2717 (9.96634e-06% of nominal)
Tolerance changes needed to achieve worst case:
R1 resistance decreased to 14250
R2 resistance decreased to 14250
R3 resistance decreased to 14250
Rf resistance increased to 1050
Rg resistance increased to 1050
C1 capacitance decreased to 7.38e-08
C2 capacitance decreased to 7.38e-08
C3 capacitance decreased to 7.38e-08