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E344 Assignment 2

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Report submitted in partial fulfilment of the requirements of the module Design (E) 344 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

September 25, 2020

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W Deyzel Voorletters en van / *Initials and surname*	September 25, 2020 Datum / *Date*

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Nomenclature

Variables and functions

mA	mili Ampere
μF	micro Farad
f_C	corner frequency in Hz
ω	corner frequency in rad/s

Acronyms and abbreviations

BPM	beats per minute
PMW	pulse width modulation

Chapter 1

System design

1.1. System overview

The purpose of this report is to document the design of a heartbeat sensor. This sensor will be powered by the same power supply as designed in report 1 [1].

As visible in the fig. 1.1 the heartbeat signal will pass through a low- and high-pass filter to remove any noise that could be misinterpreted as a heartbeat. The filtered signal gets amplified and a threshold voltage is selected. A comparator will compare the amplified signal with the threshold voltage. If the signal crosses over the reference voltage the comparator will output a high voltage, else it will output the ground level. When the comparator outputs a high voltage a heart beat was registered. The signal leaving the comparator is a PWM signal. The pulses is put through a transducer that will output a analogue signal depending on the frequency of the heartbeats.

Remaining current budget after the design of the temperature sensor is $31mA$. See chapter two for more information.

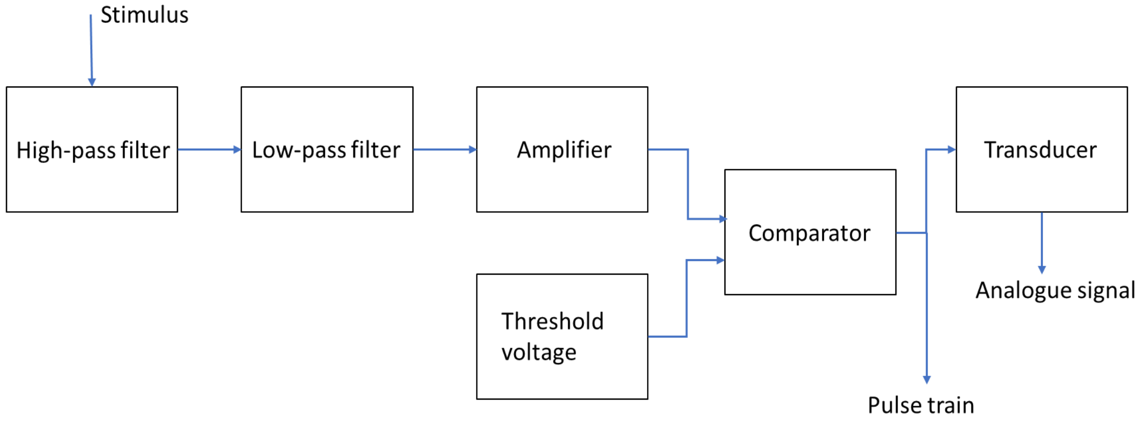

Figure 1.1: System diagram

Chapter 2

Heart rate sensor

2.1. Introduction

This chapter covers the design process of the heartbeat conditioning circuit.The project specifications require that the circuit be able to detect heart beats ranging from 50 to 150 BPM and produce a pulse for every beat that is at least $150ms$ long. The PWM signal must be converted to a analogue signal that has a range of $3.5V$ between the min and max heartbeats.

2.2. Design

According to the specifications the low cut-off frequency of 50 bpm is $0.833Hz$ and the high cut-off frequency at 150 bpm is $2.5Hz$. This is calculated by simply dividing the min and max bpm by 60. The bandwidth is $1.66Hz$. Therefore anything outside the frequency band is considered noise. It is possible that noise exist inside the frequency band but the frequency band is so small it can be ignored because it is similar to the signal. I found it very difficult to design a band-pass filter with a small enough frequency band and therefore concluded that it would be easier to design a separate low-pass and high-pass filters with cut-off frequencies mentioned above and seen in the frequency plot see fig 2.1.

fig 2.1 shows that the 150 bpm heartbeat has a frequency component of $2.5Hz$ as expected but it also has noise components at $4.8Hz$ and $7.4Hz$. This can vary but any frequency above 2.5 will be removed by the low-pass filter 2.1. The 50 bpm heartbeat has a frequency component of $0.833Hz$ as expected but it also has noise components at $1.6Hz$ and $2.5Hz$. This won't be removed by the high pass filter and will be visible in the signal as seen in C.2

The low-pass Butterworth filter transfer function eq. 2.1 as found in [2]

$$\begin{aligned} H(S) &= \frac{\omega^2}{S^2 + \frac{2}{R^2 C_1 C_2} S + \omega^2} \\ \omega^2 &= \frac{1}{R^2 C_1 C_2} \end{aligned} \tag{2.1}$$

To simplify the calculations I set the resister values equal to one another. I then picked a large resister $R = 100k\Omega$ so that the circuit draws very little current. I selected the low cut off frequency to be $2.5Hz$. Calculating C from $f_C = \frac{1}{RC}$ yields $C = 636.6nF$. Multiplying and dividing C by $\sqrt{2}$ for a optimal Q value. The capacitors C_3 and C_4 could then be calculated

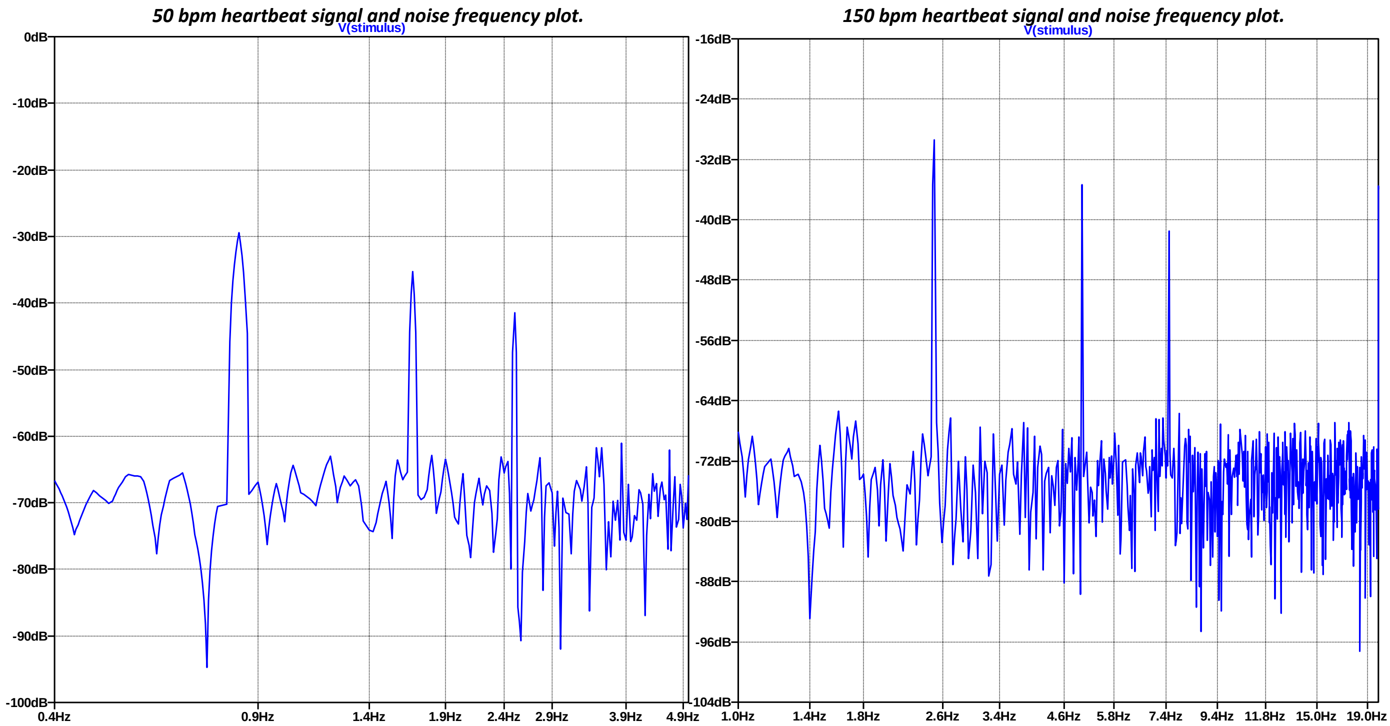

Figure 2.1: High- and low-pass frequencies with noise signals.

to be $900nF$ and $450nF$ respectively.

The high-pass Butterworth filter transfer function eq. 2.2 as found in [2]

$$H(S) = \frac{S^2}{S^2 + \frac{2}{R_2C}S + \frac{1}{R_1R_2C^2}\omega^2} \tag{2.2}$$

The design process is very similar as for the low-pass filter eq. 2.1. This time I set the capacitor values equal at $0.1\mu F$ and calculated the resister values to be $750k\Omega$ and $1.5M\Omega$ at a high-pass frequency of $0.833Hz$. Using $f_C = \frac{1}{RC}$. $R_1 = \frac{\sqrt{2}}{4C\pi f}$ $R_2 = \frac{1}{\sqrt{2}C\pi f}$. Checked with [3]

The project specification states that the heartbeat conditioning circuit including the temperature sensor must draw less than $50mA$ of current. As shows in report 1 [1] the temperature sensor draws $19mA$ of current which leaves $31mA$ for the heartbeat circuit. The fever current drawn the longer the battery can last when the device is used. The total current drawn from the conditioning circuit can be seen in fig. 2.2

The filtered signal is then amplified and compared to a threshold voltage using a comparator. A simple inverting amplifier design found on [4] is used. If the heartbeat signal crosses the threshold voltage the comparator will output a pulse otherwise it will output ground. The project specification states that the generated pulse should be at least $150ms$ in duration.

The threshold value cannot be less or more than the common mode $V_{in} - min = 1.5V$ / $V_{in} - max = 3.5V$ values for the TL0811 op-amp [5]. I chose the threshold value just above $V_{in} - min$ at $2V$. My implementation of the threshold value means that the pulse duration would be as long as the signal is above the threshold line. The duration of the pulse could be tweaked by simply adjusting the threshold value. No calculations were needed.

2.3. Results

Current drawn by the conditioning circuit as simulated in fig 2.2

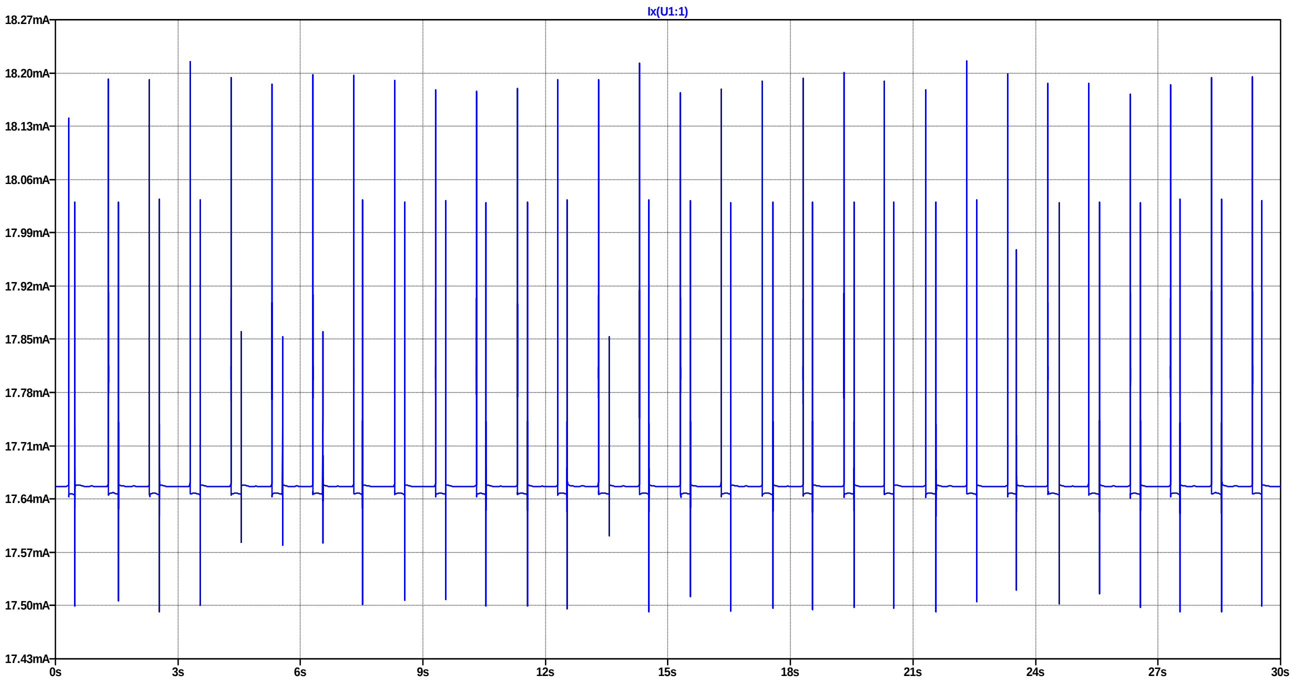

Figure 2.2: Total current drawn by conditioning circuit.

As visible in 2.2 the circuit draws around $17.6mA$. The current spikes are caused by the comparator. However, the spikes are around $500\mu A$ and is small enough to ignore.

Bode plots for the low- and high-pass filters.

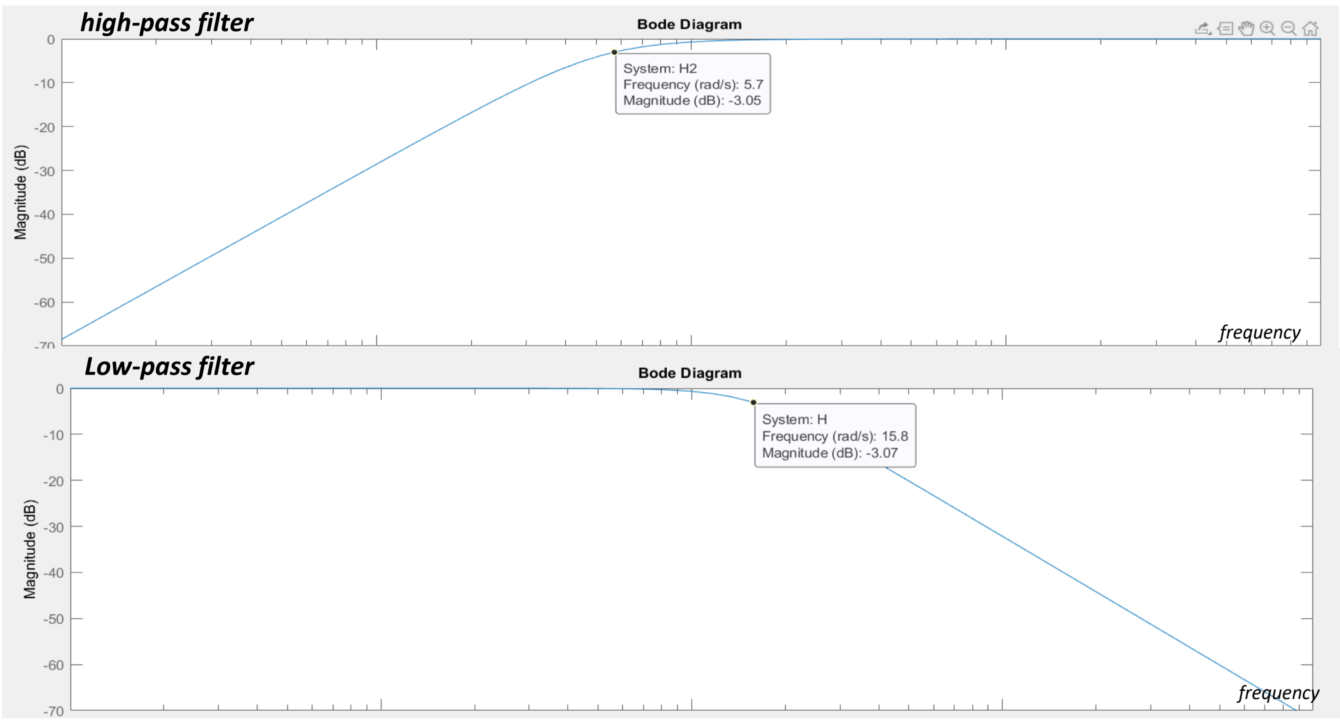

Figure 2.3: Bode plots for the low- high- pass filters

The bode plots in fig 2.3 shows the $-3dB$ frequency cut of values for the second order high-pass and low-pass Butterworth filters. My implementation has a flaw that the pass-band is not entirely flat or zero gain. A better result could be achieved with a higher order filter. It is still sufficient for this design as all the specifications are still met. See combined bode plot of the two filters in fig C.4

To confirm that the pulse duration met the project specification I only had to measure the pulse duration for the 150 BPM pulses. For it is the highest pulse frequency and would have the smallest period. The measured result can be seen below in fig 2.4

150 bpm pulse duration.

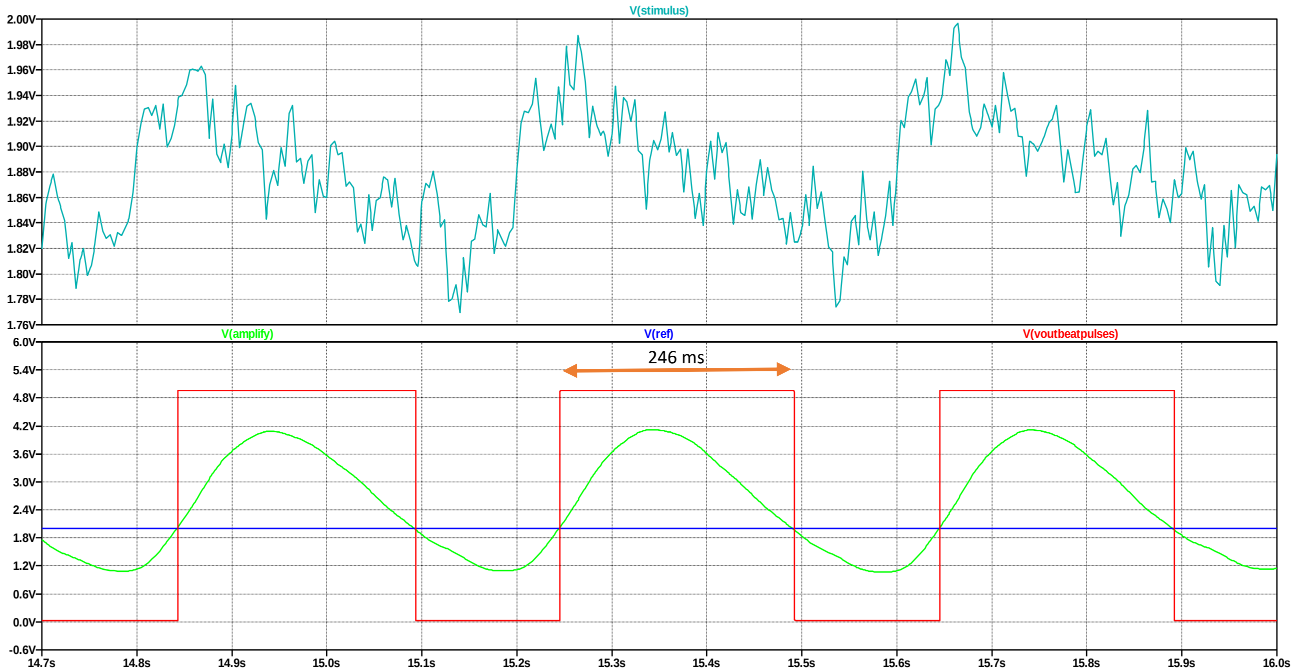

Figure 2.4: Pulse duration for 150 bpm heart beat

The specifications also require that the circuit be able to take in a signal with a $+-0.2V$ deviation in DC value and 10% deviation signal amplitude. The DC component is removed completely at the high-pass filter stage and then a controlled virtual ground is added of $2.3V$ therefore a DC change will have no effect. At 60 BPM till 150 BPM the signal amplitude deviation will also have no effect as found during testing and the circuit will work as expected. However at 50 BPM a 10% signal amplitude deviation noise component can be amplified enough to trigger a beat when there is not one.

2.4. Summary

The design meets all the project specifications listed in the project description. It works as expected as is evident in the results section. Things to keep in mind would be that the noise could set off a false beat. Even though the filters are designed to eliminated any noise harmonics it could still pass through and cause a false pulse to be produces. Especially at low heartbeats. Also, the design is only for the range of 50-150 bpm but it is possible for someone to have a heart rate lower or higher than that. The amount of current the circuit draws can also be reduced using fever op-amps. Possible solution would be to trade in the low- and high-pass filters for one pass-band filter. Maybe even design the pass-band with a gain.

Chapter 3

System and conclusion

3.1. System

The heartbeat sensor will be placed in parallel with the temperature sensor designed in report 1 [1] to make use of the same power supply. The heartbeat sensor is only designed for heartbeats ranging from 50 to 150 BPM. Future improvements would be to extend that range for it would not be accurate for someone doing a intense workout for example.

There is a lot of noise superimposed onto the signal. Low frequency noise harmonics can slip through the filter and can set off a pulse when there isn't one.

3.2. Lessons learnt

1. I learnt how to design better filters to remove noise from a signal. Specifically working with low frequencies with a small bandwidth. Specifically Butterworth filters.
2. I learnt how to convert a PWM signal to a analogue signal using a simple RC circuit. Even though I could not successfully implement it I have better understanding of how it works and that it is possible to do.
3. I never worked with a comparator before, now I have a better understanding of how it works and could use it in my design to generate pulses for a heartbeat signal.

Bibliography

[1] W. Deyzel, “Design Assessment 1 report: Temperature sensor,” 2020.

[2] J. W. Nilsson and S. A. Riedel, *Pearson*. Addison-Wesley, 2015, ch. 15.4.

[3] D. E. Resources. Sallen-key high pass butterworth filter calculator. [Online]. Available: https://www.daycounter.com/Filters/Sallen-Key-HP-Calculator.phtml

[4] ElectronicsTutorials. Operational amplifiers. [Online]. Available: https://www.electronics-tutorials.ws/opamp

[5] T. Instruments, *TL08xx JFET-Input Operational Amplifiers*, 2015.

Appendix A

Social contract

Sign and inlcude.

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E-design 344 Social Contract

2020

The purpose of this document is to establish commitment between the student and the organisers of E344. Beyond the commitment made here, it is not binding.

In the months preceeding the term, the lecturer (Thinus Booysen) and the Teaching Assistant (Michael Ritchie) spent countless hours to prepare for E344 to ensure that you get your money's worth and that you are enabled to learn from the module and demonstrate and be assessed on your skills. We commit to prepare for the module, to set the tests and assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344.

Signature: .... Date: 13 July 2020

I, Walt .... have registered for E344 of my own volition with the intention to learn of and be assessed on the principals of analogue electronic design. Despite the potential publication of supplementary videos on specific topics, I acknowledge that I am expected to attend the lectures and lab sessions to make the most of these appointments and learning opportunities. Moreover, I realise I am expected to spend the additional requisite number of hours on E344 as specified in the yearbook.

I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing respect towards the University's equipment, staff, and their time.

Signature: .... Date: 21/09/2020

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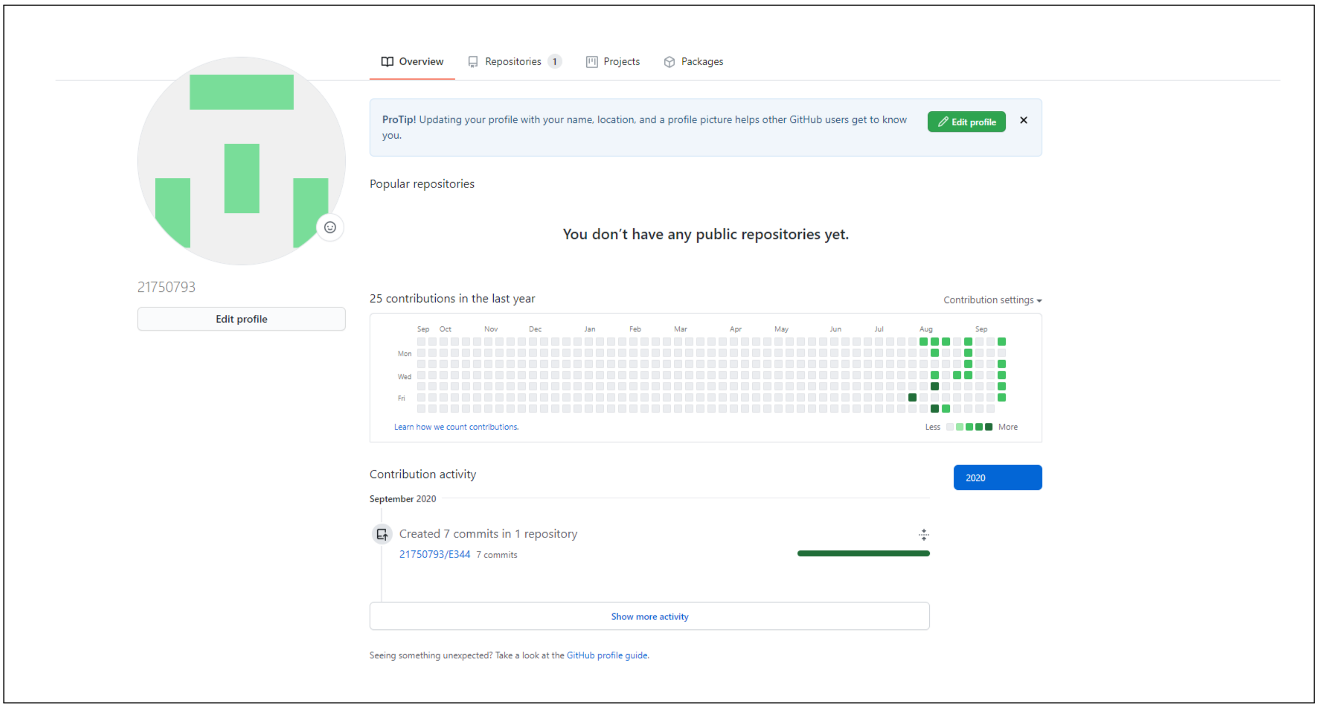
Appendix B

GitHub Activity Heatmap

Take a screenshot of your github version control activity heatmap and insert here.



Appendix C

Stuff you want to include

Each section of the conditioning circuit signal processing.

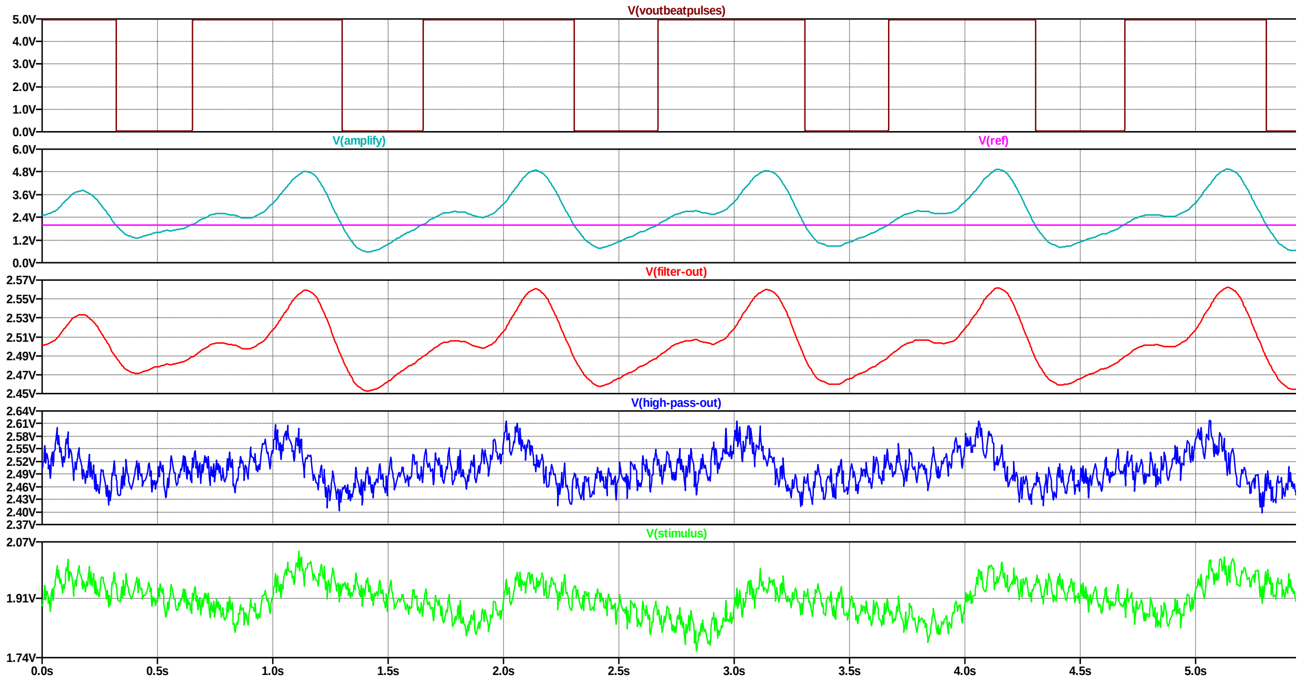


Figure C.1: Heartbeat signal processing 60BPM.

The stimulus signal (green) is passed through a high-pass filter yielding (blue) and then through a low-pass filter yielding (red). A threshold is then applied at a suitable voltage level after considering the common mode voltage of the op-amp. The output of the comparator is then a pulse train (brown).

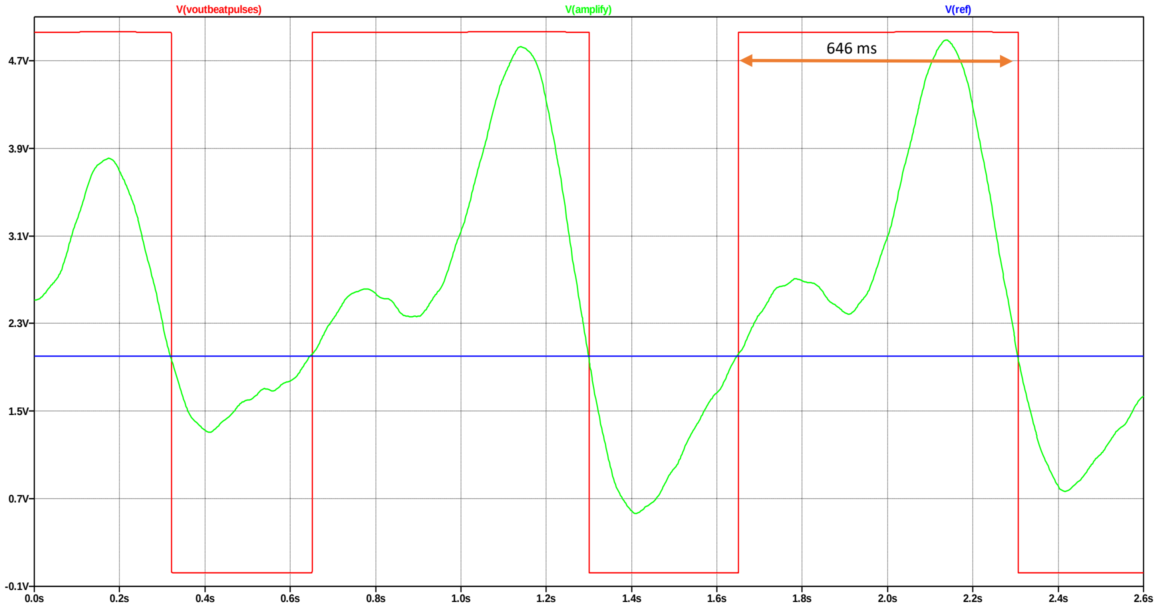


Figure C.2: Pulse duration for 50 bpm heart beat

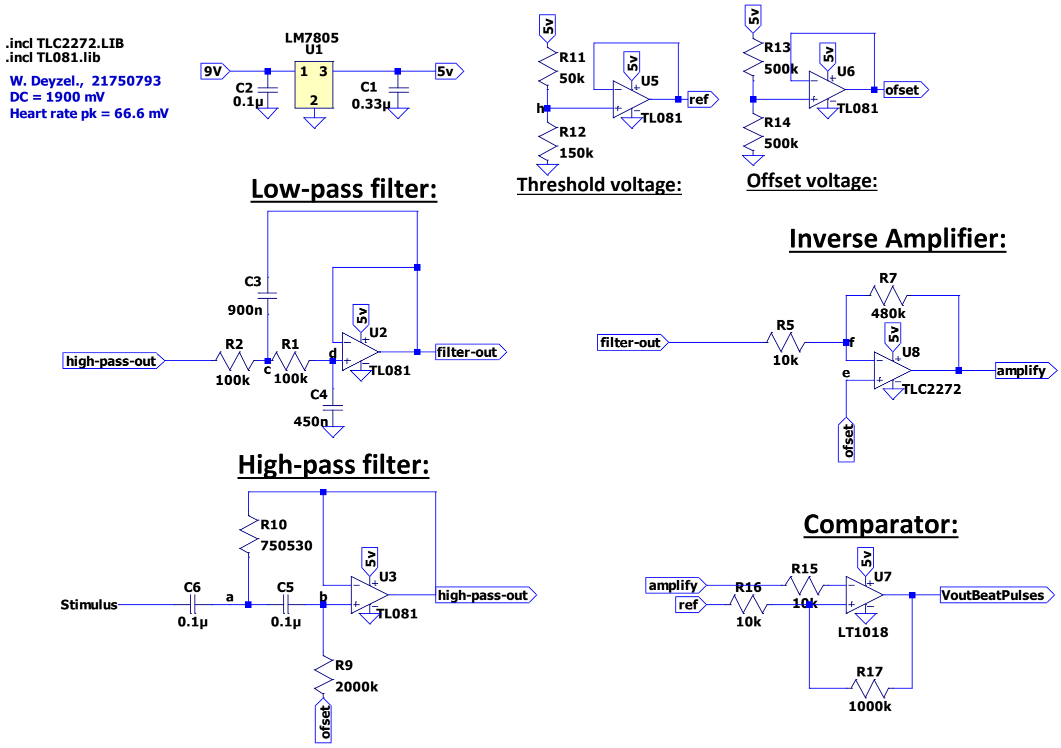


Figure C.3: Heartbeat conditioning circuit

Cut-off frequencies of high- and low-pass filters

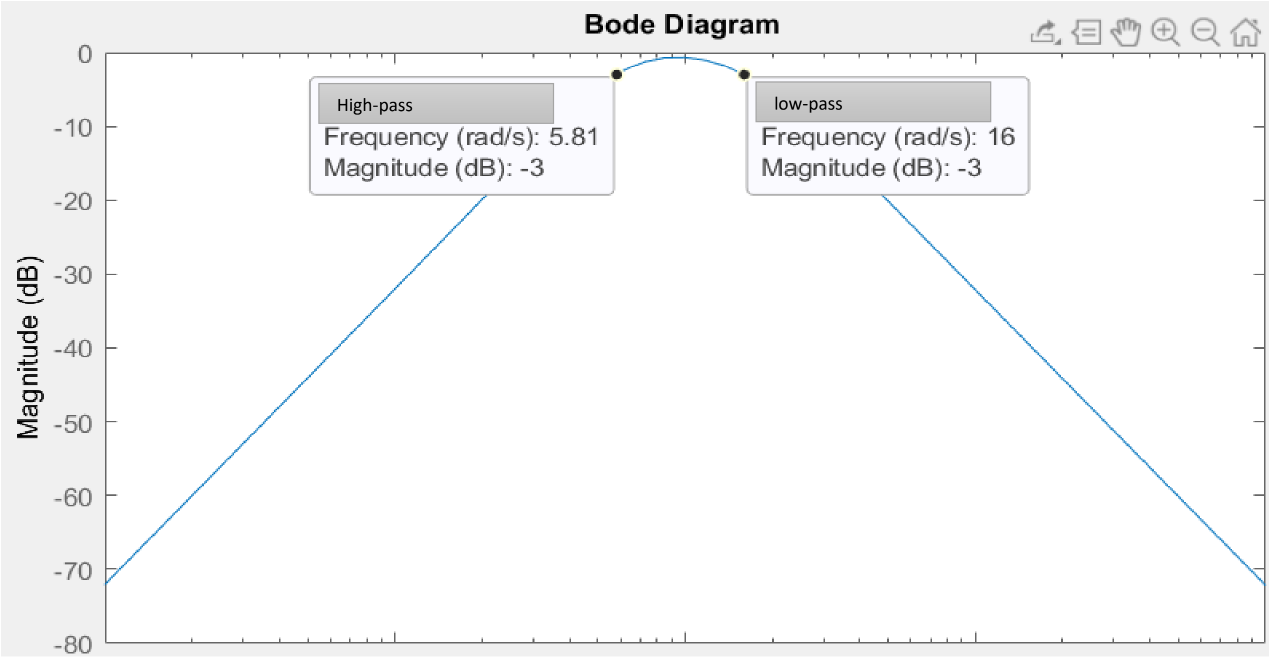


Figure C.4: Pass-band of high- and low-pass filters.

As mentioned in chapter 2 the filter does not have a flat pass-band due to the small pass-band. See fig C.4.