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E344 Assignment 3

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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.

October 25, 2020

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Nomenclature

Variables and functions

A	Gain
A	Ampere, unit for current
dB	Decibel, logarithmic value
F	Farad, unit of capacitance
f_C	Corner frequency
Hz	Hertz, unit of frequency
n	Order of filter
Ω	Ohm, unit of resistance
Q	Quality factor
s	Second, unit of time
V	Volt, unit of voltage potential
$V(0\,°\mathrm{C})$	Voltage of temperature sensor at 0 °C.
$\triangle V(1\,°\mathrm{C})$	Change of voltage at 1 °C change.

Acronyms and abbreviations

ADC	Analog to Digital Converter
BPM	Beats Per Minute
DC	Direct Current
FFT	Fast Fourier Transform
HPF	High Pass Filter
LPF	Low Pass Filter
MCU	Micro Controller Unit
VDC	Voltage DC

Chapter 1

System design

1.1. System overview

The full system diagram of the voltage regulation, temperature signal and heart beat conditioning system can be seen in Fig. 1.1, as well as the definitions of the signal lines.

A linear voltage regulator is chosen to supply the circuit with power, as it is less expensive circuitry than a switch mode regulator.

The differential amplifier is chosen to minimise op-amps needed for signal conditioning. To ensure that the 5 VDC source is not affected by the amplifier, a buffer is used in between the voltage regulator and the differential amplifier. A virtual ground offset of 2.2 V is used to center the temperature response betweeen 5 to 0 V. The last conditioning of the signal is a passive Low Pass Filter that suppresses signals of 50 Hz to 50 mV inaccuracy.

Sallen & Key high pass and low pass filters are used to filter heart beats above 50 BPM and below 150 BPM to smooth out the signal while also amplifying the signal to easily use with the comparator. The Sallen & Key filter also allows the signal to be centred around a given virtual ground no matter the signal offset. The threshold point is designed for the highest frequency signal to have a pulse larger than 150 ms. The regulator supplies ±100 mA, while the temperature sensing circuit [3] and the heartbeat conditioning circuit [4] uses ±10 mA and ±15 mA respectively. This leaves 75 mA for the rest of the MCU

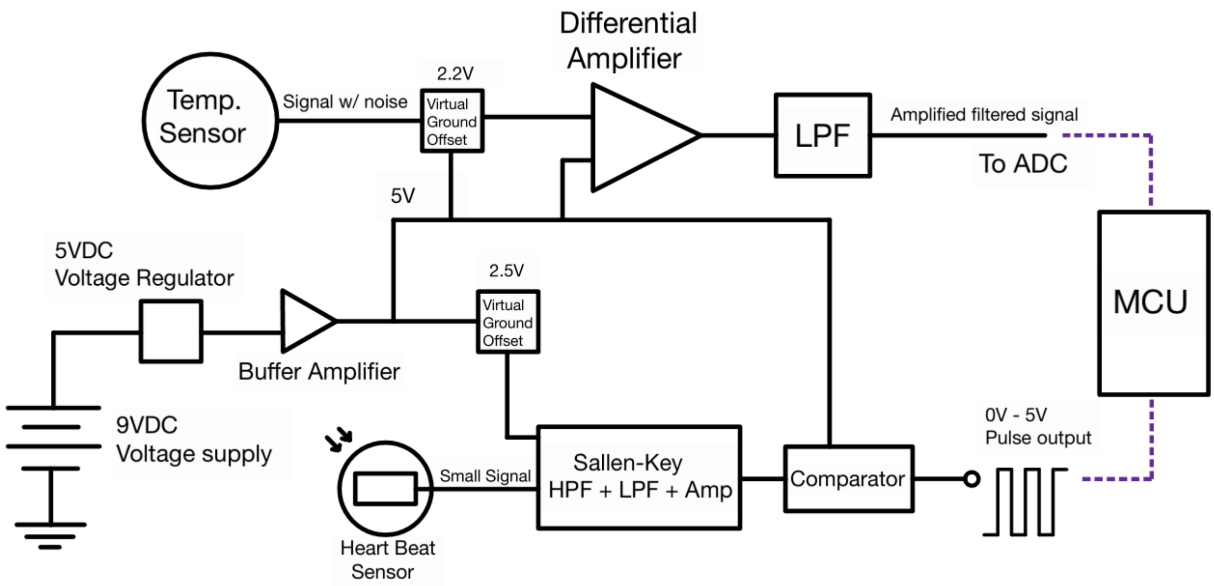


Figure 1.1: System diagram

Chapter 2

Voltage regulation

2.1. Introduction

The advantages and disadvantages of a linear regulator and a switchmode regulator will be explored in this chapter. While designing the regulator circuits, the specific datasheets for the LM7805 linear voltage regulator [1] and the LM2595 switchmode voltage regulator [2] was used to ensure the regulators are used with the correct capacitance, inductance, and resistance values. The variable voltage circuit required by the switchmode regulator [2] is a very intricate circuit, the calculations of which is described in the next section.

2.2. Design

The voltage regulator must regulate a 9 VDC supply to a stable 5 V with little to no noise.

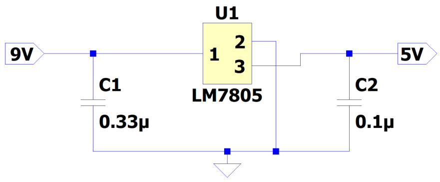
The LM7805 linear regulator circuit, as shown in Fig.2.1a, is fairly simple. It is specified in [1] that the regulator requires an input capacitance of 0.33 µF and an output capacitance of 0.1 µF to improve the transient response. Bypass capacitors are recommended to improve stability, but is not necessary if the response of the regulator is favourable enough.

The LM2595 switchmode regulator circuit, as shown in Fig.2.1b, is more complex and requires more components. The chosen circuit as stated by [2] section 9.2.2 is a series buck regulator with adjustable output, of which the values of C_{IN}, C_{OUT}, L_1, and D1 are specified as 120 µF 25-V electrolytic, 120 µF 50-V electrolytic, 100 µH and a 1N5822 3-A, 40-V Schottkey diode. The regulator is coupled with a Post Ripple filter, comprised of a series inductor of 3 µH and a 15-V bypass capacitor of 180 µF, to reduce the ripple to half. This section includes the formulas needed to work out the values of the other components. R_1 is chosen as 1 kΩ and V_{REF} is specified as 1.23 V.

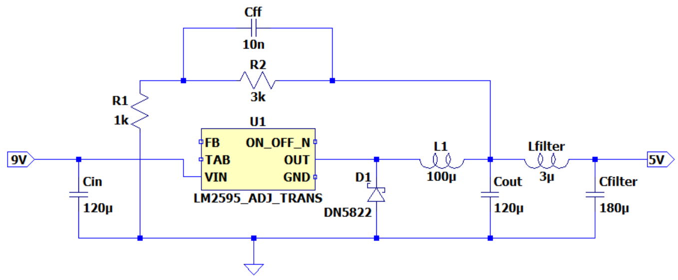
$$R_2 = R_1(\frac{V_{OUT}}{V_{REF}} - 1) = 1\,\mathrm{k\Omega}(\frac{5\,\mathrm{V}}{1.23\,\mathrm{V}} - 1) = 3.06\,\mathrm{k\Omega} \approx 3\,\mathrm{k\Omega}$$

$$C_{FF} = \frac{1}{31 \times 10^3 \times R_2} = \frac{1}{31 \times 10^3 \times 3\,\mathrm{k\Omega}} = 10.75\,\mathrm{nF} \approx 10\,\mathrm{nF}$$

To measure the voltage, current, power, and efficiency, the `LTSpice` function `.meas` is used (Fig.2.3).



(a) Linear voltage regulator.



(b) Switchmode voltage regulator.

Figure 2.1: Circuit diagrams of the two voltage regulators

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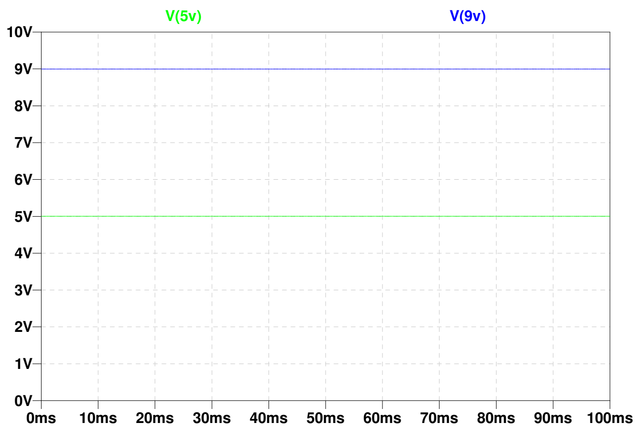
2.3. Results

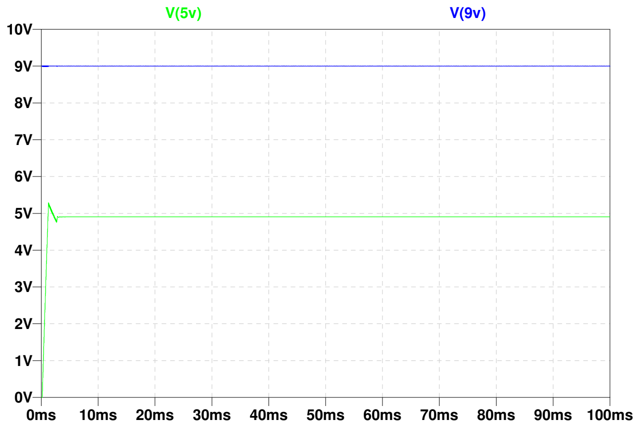
The voltage response for the two voltage regulators can be seen in Fig. 2.2. The results are compared in Table 2.1



(a)

```
pout: AVG(v(5v)*i(r_load))=0.500554 FROM 0 TO 0.1
pin: AVG(-v(9v)*i(r_sense))=0.945436 FROM 0 TO 0.1
eff: pout/pin=0.529442
iout: AVG(i(r_load))=0.100055 FROM 0 TO 0.1
iin: AVG(-i(r_sense))=0.105061 FROM 0 TO 0.1
```

(b)



(c)

```
pout: AVG(v(5v)*i(r_load))=0.473501 FROM 0 TO 0.05
pin: AVG(-v(9v)*i(r_sense))=0.587227 FROM 0 TO 0.05
eff: pout/pin=0.806335
iout: AVG(i(r_load))=0.0968337 FROM 0 TO 0.05
iin: AVG(-i(r_sense))=0.0652632 FROM 0 TO 0.05
```

(d)

Figure 2.2: Voltage regulation, comparing the linear and switchmode regulators... (a) Linear regulator voltage response (b) Linear Regulator `.meas` results. (c) Switchmode regulator voltage response (d) Switchmode regulator `.meas` results.

```
.meas Pout AVG V(5V)*I(R_load)
.meas Iout AVG I(R_load)

.meas Pin AVG -V(9V)*I(R_sense)
.meas Iin AVG -I(R_sense)

.meas Eff param Pout/Pin
```

Figure 2.3: `.meas` arguments used in `LTSpice`

Table 2.1: Table of current, power and efficiency.

	Current		Power		Efficiency
	Supplied [mA]	Draw [mA]	Supplied [mW]	Draw [mW]	[%]
LM7805 Linear	105	100	945.44	500.55	52.94
LM2595 Switchmode	65.26	96.83	587.23	473.5	80.63

Table 2.2: Table of Absolute maximum ratings.
Based on the datasheet of LM7805 in [1] and LM2595 in [2]

	Maximum Allowed Input [V]	Dropout Voltage at 25 °C [V]	Maximum Power Dissapation [W]
LM7805 Linear	30	1.7	≤ 0.75
LM2595 Switchmode	45	0.88	Limited Internally

From the figures and tables it is seen that both regulators have advantages and disadvantages.
The LM7805 regulator has a more favourable response, a higher dropout voltage, and less expensive components, but is not very efficient in terms of power.
The LM2595 regulator is much more efficient and has a higher maximum allowed input, but is much more expensive in terms of components and circuit real estate, and only allows the circuit to reach the desired output after a certain time. As for maximum ratings, the LM7805 linear regulator has a high enough power ceiling that it won't cause any problems for the circuit.

2.4. Summary

From the results, the chosen design is the LM7805 linear regulator. Although not as efficient, it is less expensive, has a higher dropout voltage and better voltage response, which is important for it's use with a temperature sensor, where noise is already a big problem.

Chapter 3

Temperature sensor conditioning circuit

3.1. Intro

A temperature sensor needs a conditioning circuit that will allow the output of the sensor to be read by a micro-controller's ADC. This chapter will explain in detail how this circuit will be designed to meet the specific requirements of the temperature sensor and the ADC. The design process is aided by the formulas found in [5] and circuit descriptions in [6].

3.2. Design

The following parameters of the temperature sensor are specified as:

$$V(0\,^{\circ}\mathrm{C}) = 620\,\mathrm{mV}; \quad \triangle V(+1\,^{\circ}\mathrm{C}) = +20\,\mathrm{mV}$$

There are a couple of design requirements that must be adhered to. The circuit shall:

- measure the output through the full range of 34 to 42 °C which corresponds to a swing of greater than 3.2 V
- suppress 50 Hz noise of 10 mV amplitude to an accuracy of less than 80 mV
- use less than 25 mA
- have a step response of less than 100 ms for a ±1 °C change.
- simulate under 2 minutes in `LTSpice`.

From the parameters and the requirements, a linear equation can be formulated to used with [5] to design the first steps of the differential amplifier circuit. Choosing R_f as 82 kΩ.

$$y = 20x + 1.38$$

$$m = 1 + \frac{R_f}{R_g}; \quad R_g = \frac{R_f}{m-1} = \frac{82\,\mathrm{k\Omega}}{20-1} \approx 4.3\,\mathrm{k\Omega}$$

To determine the values of the voltage divider before the buffer, a divider circuit must be calculated from R_g as if the buffer is not there. From these values, R_1 and R_2 can be calculated. V_{ref} is equal to 5 V

$$R_{g2} = \frac{R_g}{10} \approx 430\,\mathrm{k\Omega}; \quad R_{g1} = R_g - R_{g2} \approx 3.8\,\mathrm{k\Omega}$$

$$V_{ref'} = \frac{|b| \times R_{g1}}{R_{g1} + R_f} = 62\,\mathrm{mV}; \quad R_1 = \frac{R_{g2}(V_{ref} - V_{ref'})}{V_{ref'}} \approx 33\,\mathrm{k\Omega}$$

$$R_2 = \frac{V_{ref'} \times R_1}{V_{ref} - V_{ref'}} \approx 430\,\Omega$$

The main op-amp is required to have a full swing around 5 to 2 V, thus the TLC2272 Op-Amp is best suited for this part of amplification as it can properly go between the rails as specified in [7]. As for the buffer, it isn't necessary to swing at all and only has a unity gain, thus the TL081 would suffice as it has high slew rates [8].

To use the whole swing of the amplifier, a virtual ground must be applied to the temperature signal. A simple voltage divider using 2 resistors of 82 kΩ can be used to achieve this, along with a capacitor and tuning resistor that will allow the amplified response to center around the virtual ground more effectively. The voltage divider network should give a 2.5 V virtual ground. The capacitor also helps to slightly filter the input going into the differential amplifier, but is not necessary for filtering the signal, only to store the voltage drop.

Lastly the output must be filtered to achieve the desired noise suppression. The noise of 10 mV is now amplified 200 mV. The noise needs to be suppressed by at least −7.9 dB in order to achieve the 80 mV accuracy. Fortunately, a standard Low Pass Filter can be designed in `LTSpice` and adjusted to achieve the desired suppression. After the suppression is achieved, the filter will be tested to see if it still meets the step response requirement. For 50 Hz and $R_o = 20\,\mathrm{k\Omega}$ the capacitance is calculated as:

$$C_o = \frac{1}{2\pi \times f_c \times R_o} = \frac{1}{2\pi \times 50 \times 20\mathrm{k}} \approx 160\,\mathrm{nF}$$

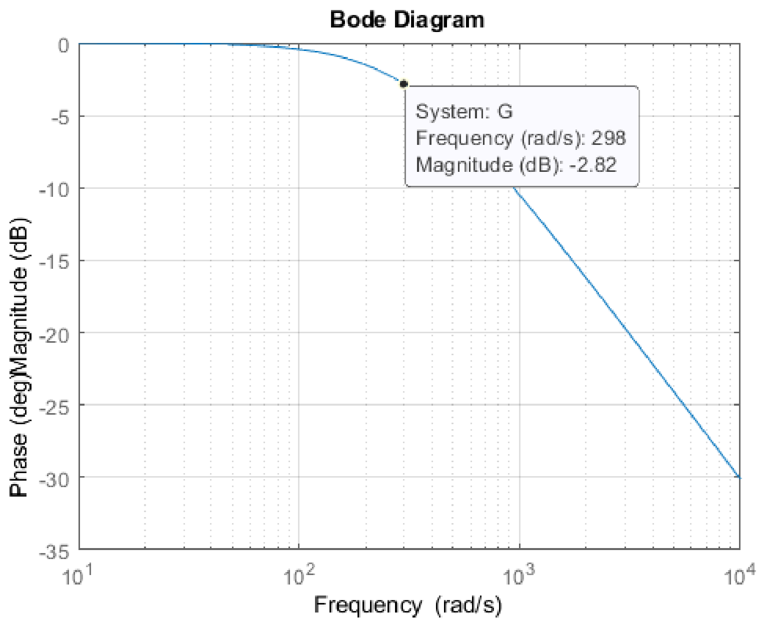


Figure 3.1: LPF Bode Plot

3.3. Results

The response of the system can be seen in Fig.3.3. Once again, the current draw is measured using the `.meas` command in `LTSpice`.

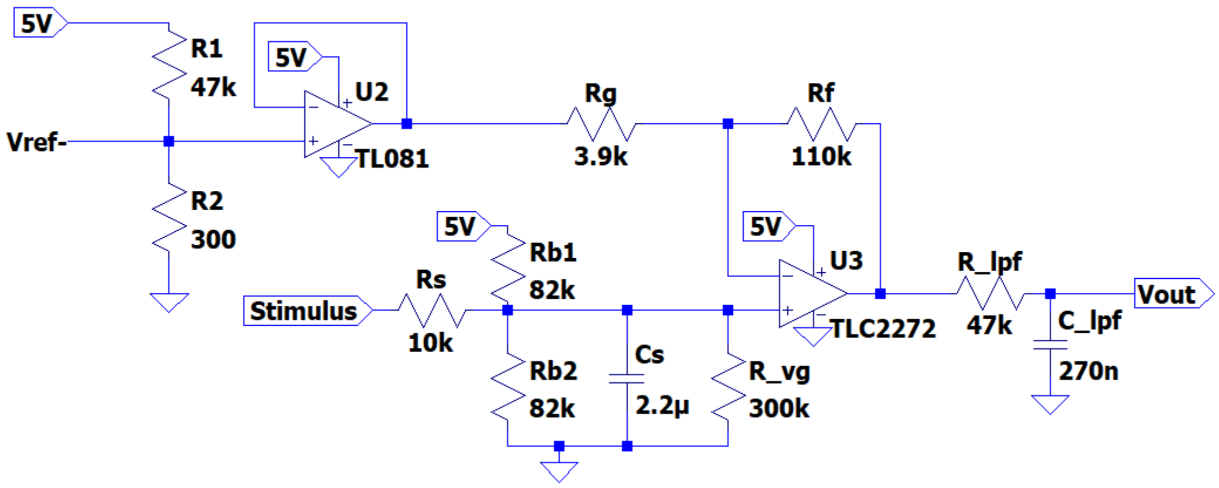


Figure 3.2: Final Differential Op-amp circuit

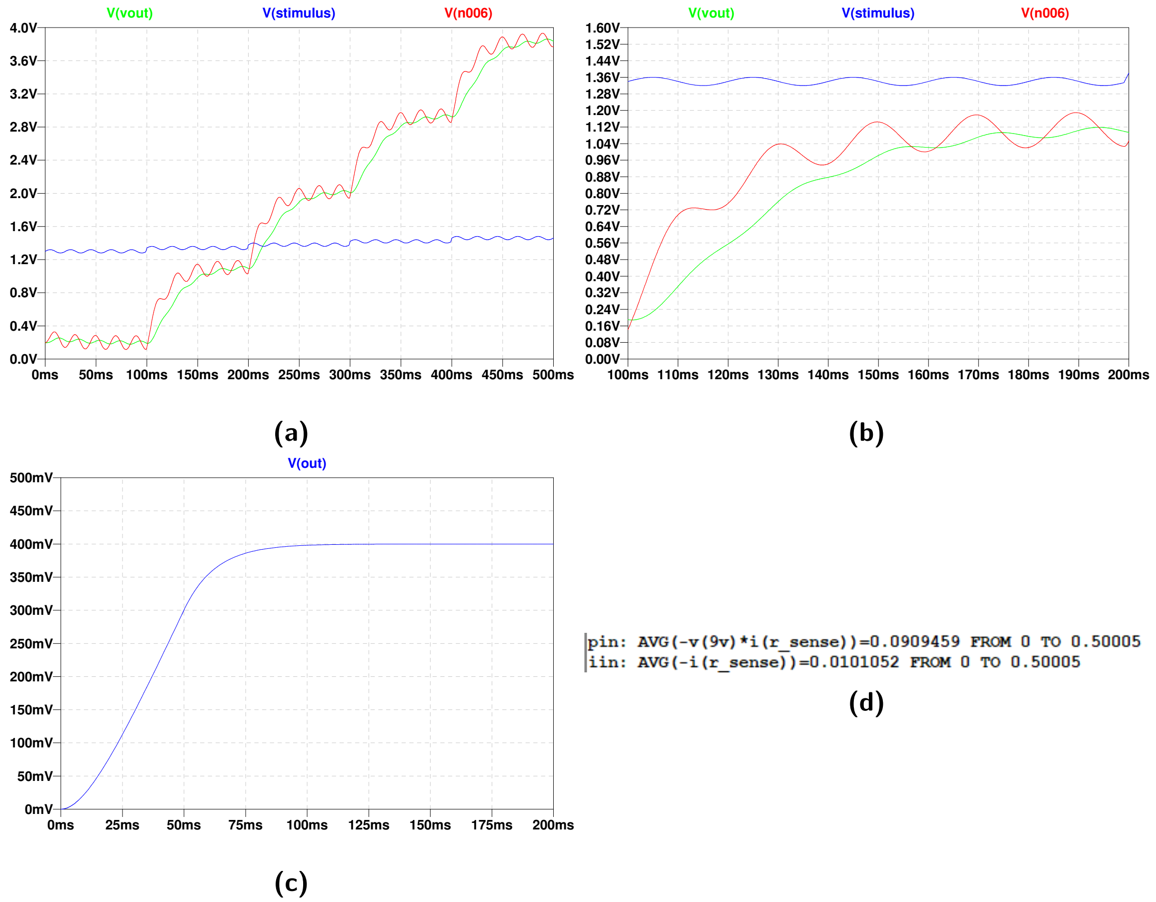


Figure 3.3: Temperature Condition Circuit outputs..(a) Output vs Input vs Unfiltered Output (b) Zoomed 100ms partition of 3.3a (c) Simulated LPF response (c) Circuit total current draw `.meas` results

Table 3.1: Table of time taken to finish simulation

Simulation Time-frame	Total Simulation Elapsed Time
500 ms	3.954 s

From the results it can be seen that the circuit meets the requirements. From Fig.3.3a it can be seen that the circuit takes advantage of the full swing of the op-amp. allowing a response between roughly 3.8 to 0.2 V. In Fig.3.3b it can be seen that the circuit achieves the 100ms rise time as set out bu the requirements. The LPF adheres to the step response as well in Fig.3.3c. The circuit draws less than 15 mA on average and simulates under 2 minutes on the machine used.

3.4. Summary

In summary, the circuit adheres to the requirements, while also improving on some. The output swing is greater than the designed 3.2 V and only uses 10.1 mA. Although the rise time of the LPF could be designed to be more responsive, it meets the requirements without the need of a more complex LPF like a Butterworth-filter. This circuit meets the requirements all while only using 2 op-amps.

Chapter 4

Heart rate sensor

4.1. Introduction

In this chapter, the design for the Sallen & Key HPF, LPF and comparator will be explained and what sources where consulted in the designed process.

The Sallen & Key HPF and LPF design [9] can be used to not only filter the signal above a desired frequency, but by adding a resistor feedback the signal can also be amplified. Amplification reduces the quality of the signal (Q), thus the amplification must not be too large . This method is used in the design to make it easier for thresholding in a later stage as the signal is large enough for small thresholding changes.

4.2. Design

Before designing the filter, the frequency response must first be inspected to determine which frequencies are desired and which are not. In Fig 4.1 a 150 BPM heart beat is drawn in `LTSpice` using it's built in FFT function, and shows 3 prominent frequencies between 0.8 Hz and 4 Hz and numerous spikes above 10 Hz. From this it can be concluded that the frequencies from 0.8 to 4 Hz are the desired signals while anything above or below this range is noise.

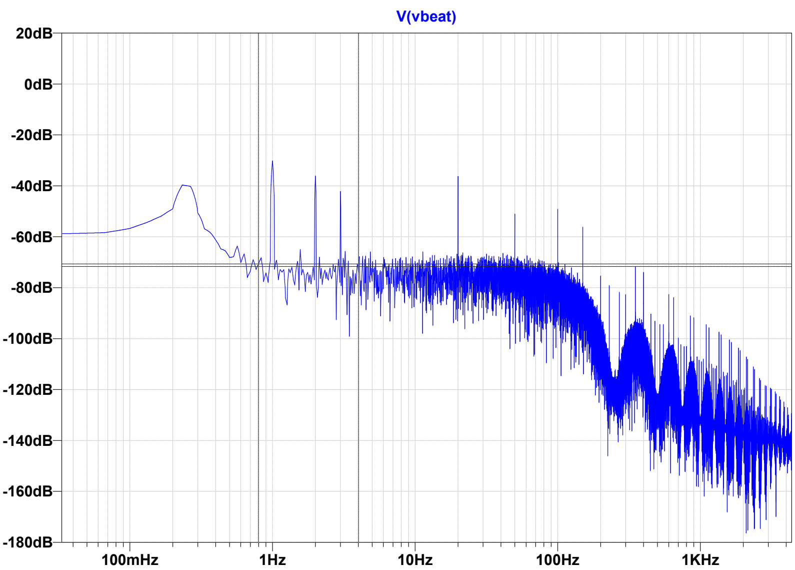
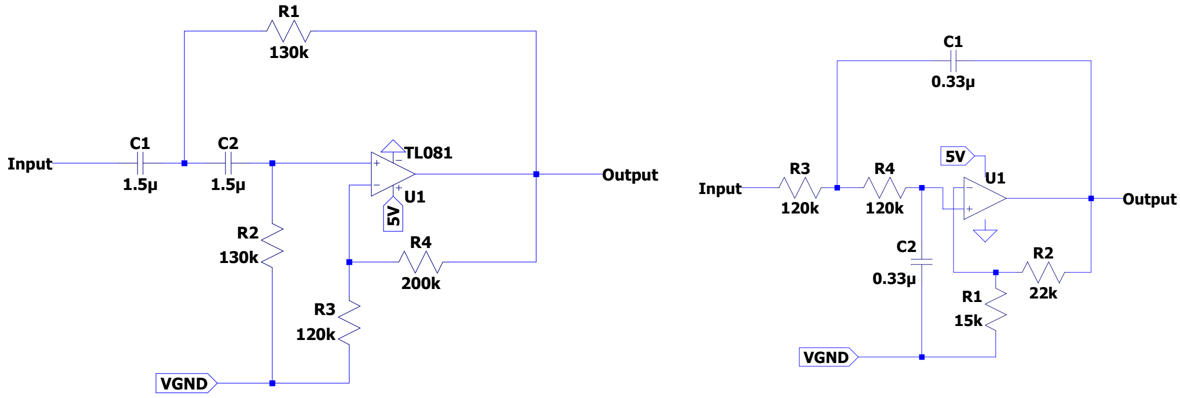


Figure 4.1: FFT of a 150BPM heart beat signal

The HPF will thus be designed to suppress all frequencies below 0.8 Hz. The design layout



(a) Sallen & Key HPF circuit diagram

(b) Passive LPF circuit diagram

Figure 4.2: Circuit Diagrams of a Sallen & Key HPF and LPF

will look like Fig. 4.2a. The HPF will be designed for a corner frequency (f_c) of 0.8 Hz. One can assume $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then Eq. 4.1 becomes Eq. 4.2. Using a standard capacitor value of 1.5 µF for C, a resistor value can be approximated.

$$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} \tag{4.1}$$

$$f_c = \frac{1}{2\pi RC} \tag{4.2}$$

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 0.8 \times 1.5\mu} = 132\,629\,\Omega \approx 130\,\mathrm{k}\Omega$$

To finish off the design of the HPF, the amplification factor must be designed. As noted in [9] the amplification is dependant on the quality factor, Q, which determines the amplification. Designing for a moderate quality factor of 1.8 gives the amplification and resistor values for R_3 and R_4 as follows in Eq. 4.3 and Eq. 4.4. Assume $R_4 = 22\,\mathrm{k}\Omega$.

$$A = \frac{3Q-1}{Q} = \frac{3(1.8)-1}{3} = 2.444 \tag{4.3}$$

$$A = 1 + \frac{R_4}{R_3} \implies \frac{R_4}{R_3} = 1.444$$

$$R_3 = \frac{R_4}{1.444} = 15.235\,\mathrm{k}\Omega \approx 15\,\mathrm{k}\Omega \tag{4.4}$$

The LPF will be designed to suppress all frequencies above 4 Hz. The design layout, seen in Fig. 4.2b, looks similar to the HPF. Using the same design equations for the HPF, the resistor values can be calculated. The feedback resistor network for amplification is the same as for the HPF Now the resistor values for the LPF can be designed using 4.1 and 4.2, assuming that $R_5 = R_6 = R$ and $C_3 = C_4 = C = 0.33\,\mu\mathrm{F}$.

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 4 \times 0.33\mu} = 120.572\,\mathrm{k}\Omega \approx 120\,\mathrm{k}\Omega$$

A simple comparator design, seen in Fig. 4.3, that only uses an op-amp will be used to push the signal from 0 to 5 V. The threshold value is determined by R_7 and R_8. As the signal through the HPF is already centred around 2.5 V, any deviation in the DC component of the signal is neglected. Assuming the filtered response of a heartbeat will approximate a sawtooth signal centred around 2.5 V, the comparator must be designed for the highest frequency as it will have the shortest pulse. A 150BPM signal will subsequently have a period of 400 ms. For simplicity, the thresholding can first be designed for 200 ms, or approximately 2.5 V. To achieve this, R_7 and R_8 must be equal. The thresholding should be large enough to allow for a deviation of ±10 mV in amplitude, while also eliminating the need for a One Shot component. The resistors must also be large enough to limit current draw. Thus $R_7 = R_8 = 330k$. A second resistor, R_9, can be placed beneath R_8 to adjust the thresholding value to fit the signal needs of 150 ms

Regarding op-amps, the HPF and LPF handles a small input voltage with a relatively small swing. For this stage, the op-amps will never reach the 0 to 5 V rails, and can therefore use a TL081 op-amp [8]. The comparator however, will receive an larger, amplified signal and will need to push the voltage between the 5 V and 0 V rails, therefore needing a much stronger op-amp, such as the TLC2272 op-amp [7].

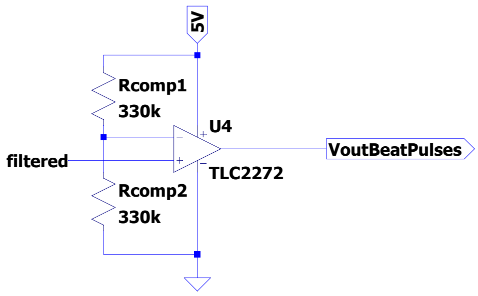


Figure 4.3: Op-amp comparator circuit

4.3. Results

Fig. 4.4 shows the results of the filter responses. The HPF & LPF reacts as expected, giving an amplification at around 0.8 Hz that can be seen in Fig. 4.4a and at around 4 Hz seen in Fig. 4.4b. The combined system response is seen in Fig. 4.4c

The analysis for the thresholding of the comparator and and pulse duration is seen in Fig. 4.5. The output filtered signal is measured at the threshold voltage at which the comparator will trigger shown Fig. 4.5d and the output signal at 60 BPM in Fig. 4.5a as well as 150 BPM in Fig. 4.5b. The ideal thresholding value was found using 18 kΩ for R_9.

The current draw from the power supply is measured at 60 BPM and 150 BPM and shown in Table 4.1.

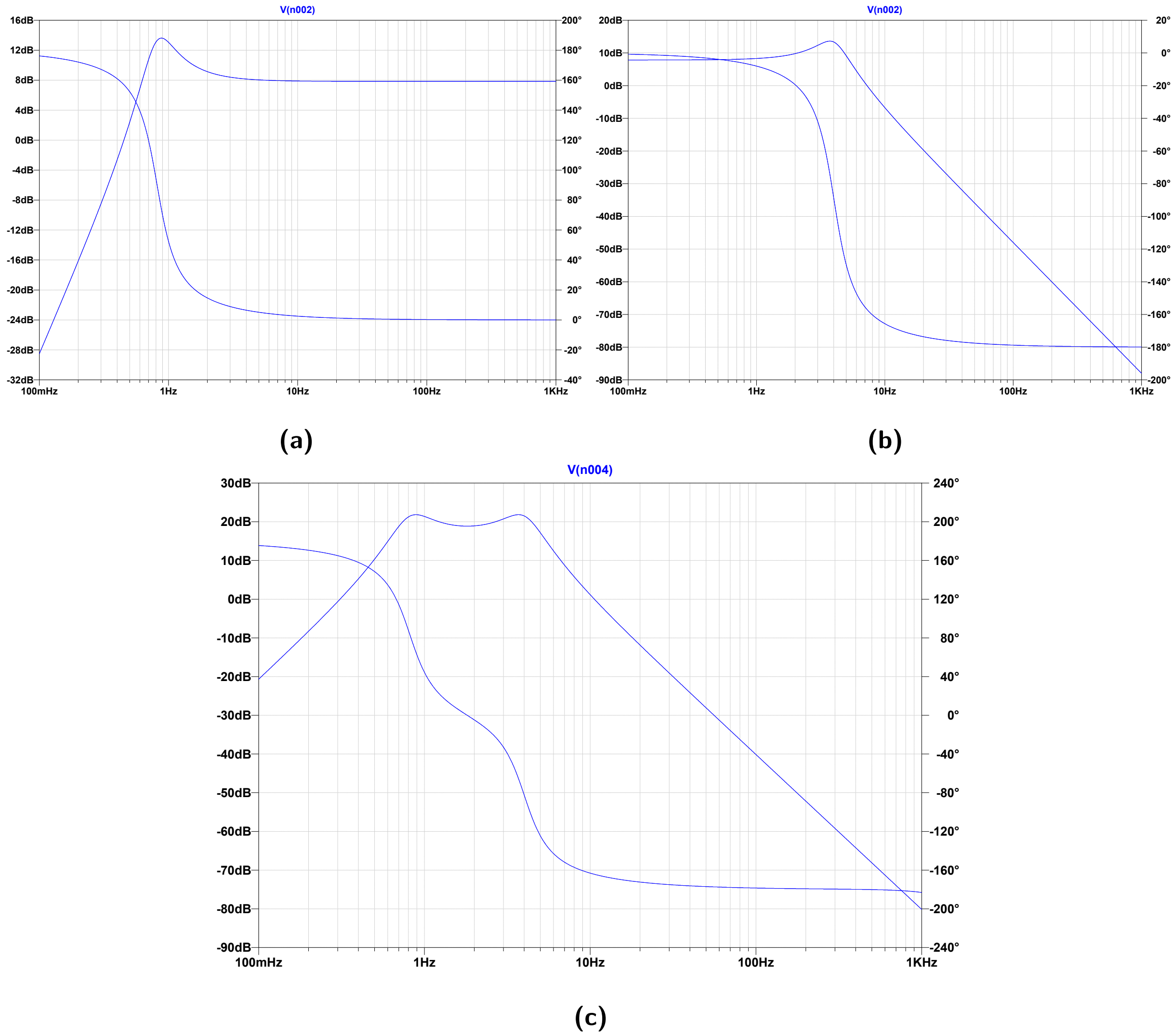


Figure 4.4: Bode plots of filter stages. (a) HPF Sallen Key bode plot (b) LPF Sallen Key bode plot (c) Combined stages bode plot

Table 4.1: Table of current usage.

Test frequency $[BPM]$	Current through R_{sense} [mA]
60	-15.0232
150	-15.0232
Average	-15.0232

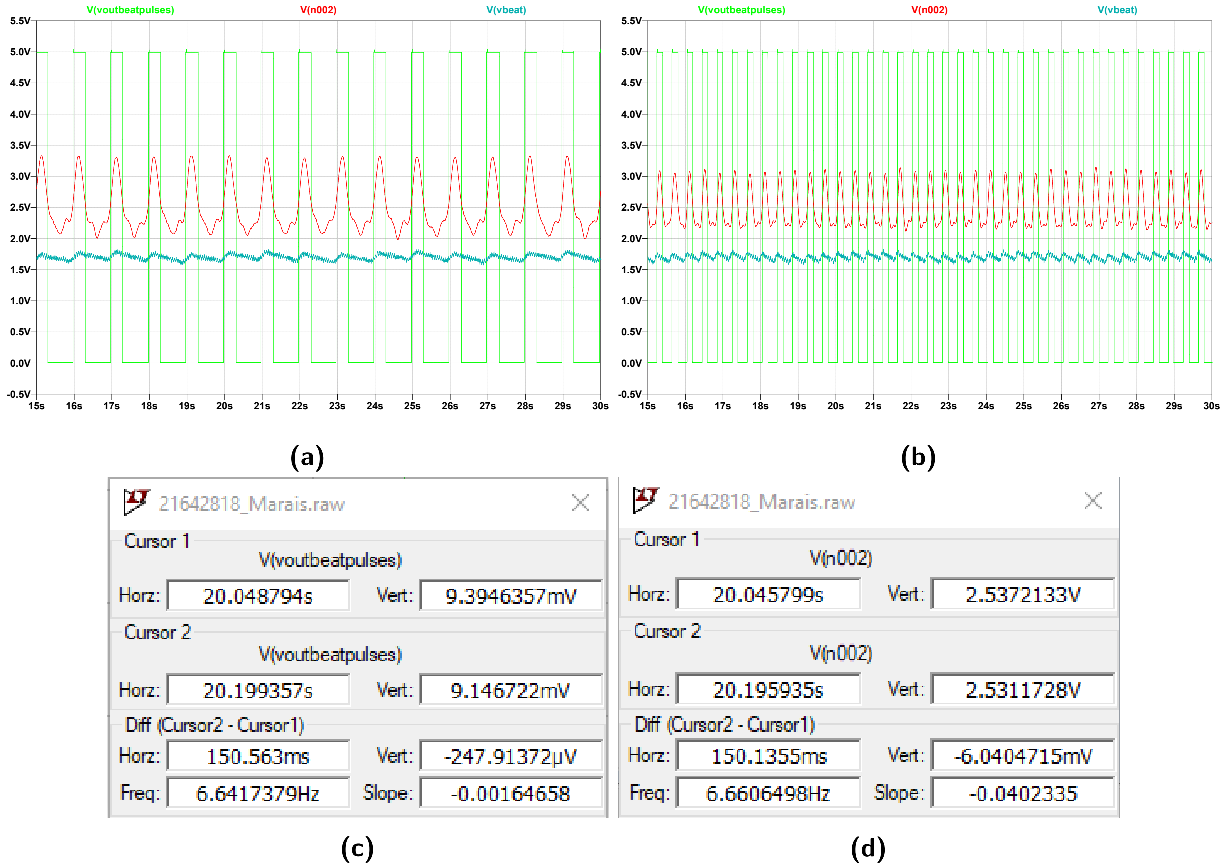


Figure 4.5: (a) 60 BPM signal with pulse output (b)150 BPM signal with pulse output (c) Cursor position for pulse duration in Fig. 4.5b (d) Cursor position for threshold values

4.4. Summary

The circuit performed as expected. The pulse duration for the shortest wavelength still exceeds 150 ms and the comparator pushes the signal to reach 5 to 0 V at its highest and lowest. Small deviations in amplitude and in DC offset is also limited which ensures the signal is stable. The circuit is limited to only work efficiently between the ranges of 50 to 150 BPM, as any BPM lower or higher might be filtered out. One must keep in mind that the circuit is only truly accurate after approximately 1 s at 50 BPM as the capacitors used for filtering needs to be charged.

Chapter 5

Calibration and digitisation

5.1. Temperature sensor

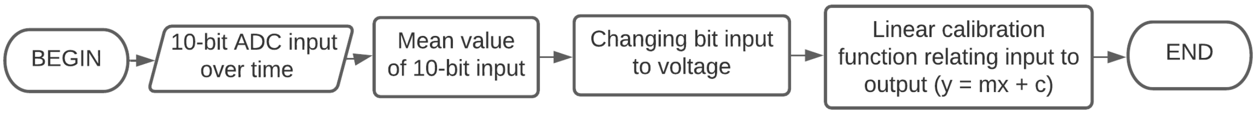


Figure 5.1: Temperature Sensor Flow Diagram

5.1.1. Analytical Design

The expected output voltage can be approximated by Eq. 5.1 using adjusted values from Ch.3.2. These values can be used to determine the 10-bit ADC values for the range of temperatures to set up a linear calibration equation (Eq. 5.3) for the temperature sensor conditioning circuit.

$$V_{out} = G \cdot [(\alpha \cdot T + V_{so}) - V_{offset}] + V_{gnd} \tag{5.1}$$

$$ADC = V_{out} \cdot \frac{2^N}{V_{ref}} = V_{out} \cdot \frac{2^{10}}{5} \tag{5.2}$$

Table 5.1: Table of analytical output

Temp °C	34	36	38	40	42
V_{out}	0.6	1.4	2.2	3	3.8
ADC Value	122	286	450	614	778

$$T = 0.012195122 \times ADC + 32.51219512 \tag{5.3}$$

5.1.2. Empirical Design

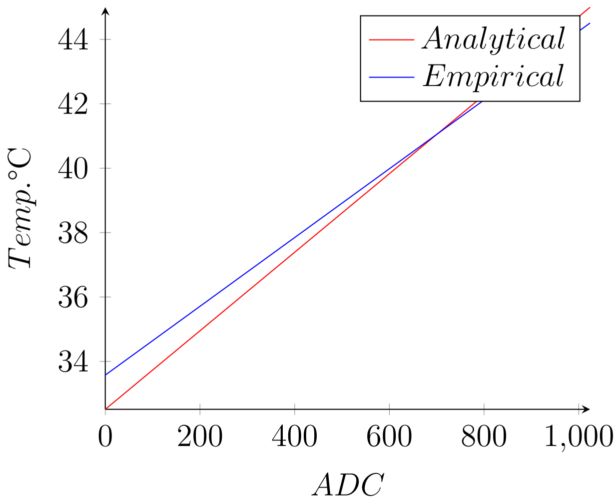
From the measurements made using the temperature conditioning circuit, the calibration equation can be adjusted.

Table 5.2: Table of analytical output

Temp °C	34	36	38	40	42
Measured ADC Value	40	227	414	602	789

$$T = 0.010678043 \times ADC + 33.57573068 \tag{5.4}$$

The analytical design is a reasonably close approximation, but had a quite large margin of error.



5.2. Heart rate sensor

The heart rate sensor output is measured over 6 s. For this input, a "for" loop runs through all the data points in the time and amplitude domain, storing all rising edge time data points in a list. Eq. 5.5 can be used to calculate BPM. From the results in Table 5.3 the linear calibration function can be written as Eq. 5.6.

$$BPM = \frac{Edges \times 60}{Time} \tag{5.5}$$

Table 5.3: Table of BPM output for input

BPM In	50	70	90	110	130	150
BPM Out	51.3347	70.7547	90.0732	109.7093	129.7064	149.4396

$$BPM_{out} = 1.016707587 \times BPM_{in} - 1.861021767 \tag{5.6}$$

Chapter 6

System and conclusion

6.1. System

The circuit works as expected. The temperature conditioning circuit properly uses an adequate voltage range, increasing the accuracy of the sensor and especially when used with the 10-bit ADC of the MCU. The filter coupled to the circuit keeps the inaccuracy between an acceptable range while also reaching the proper voltage after the required 2 s wait time. The temperature circuit using the ADC has a resolution of 0.0101 °C per bit.

The heart rate sensor conditioning circuit fits nicely into the system. The MCU can easily read the pulse inputs and count every high pulse for a duration of time and then relate that to BPM. This will only need one pin from the MCU, while also using very little current. The circuit is effective and makes accurate pulses. In the way the circuit is built, it also allows it to be used with any DC offset from the heart beat sensor, given that it is between the ranges of 0 to 5 V.

The calibration of the temperature and heart beat outputs are calibrated to stay within ±1 °C and ±1 BPM accuracy. The code used for the calibration is very simple and should be very fast to generate an output.

For the current supplied by the voltage regulator, the total circuit only uses ≈ 25 mA which leaves a lot of current left for the MCU.

6.2. Lessons learnt

Things that I learned:

- Most importantly, I feel much more confident in my knowledge of LaTeX and `LTSpice` and have learned hwo to use them properly, while also finding out how they are limited in certain aspects.
- I learned how to implement filters in a more effective way,and how different filters can be used for different use cases.
- I learned that you can build a lot of simple components like One-Shot timers, comparators and filters only by using op-amps, resistors and capacitors.
- I learned that it is always wiser to start early and not procrastinate. Also, write down while you are designing so that you can always backtrack and find your steps.

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Appendix A

Social contract

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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, Gerhardus Magnus Marais 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.

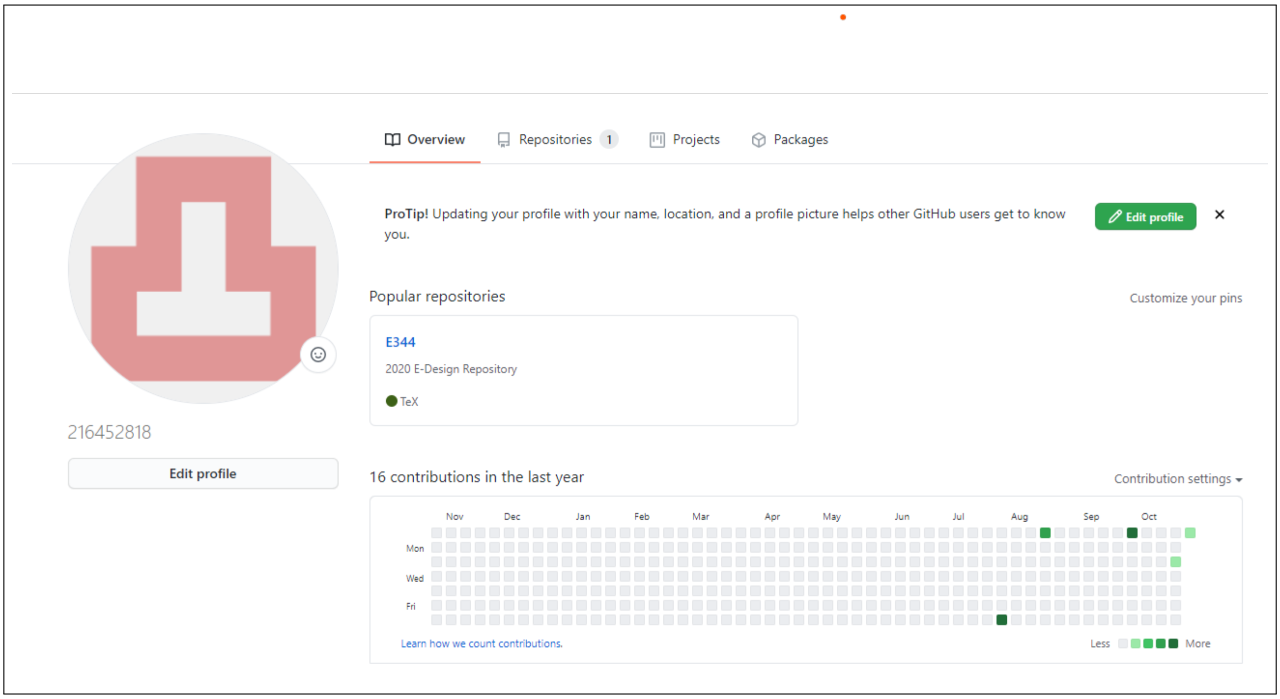
I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing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

Signature: .... Date: 23/10/2020

1

Appendix B

GitHub Activity Heatmap



Appendix C

Stuff you want to include

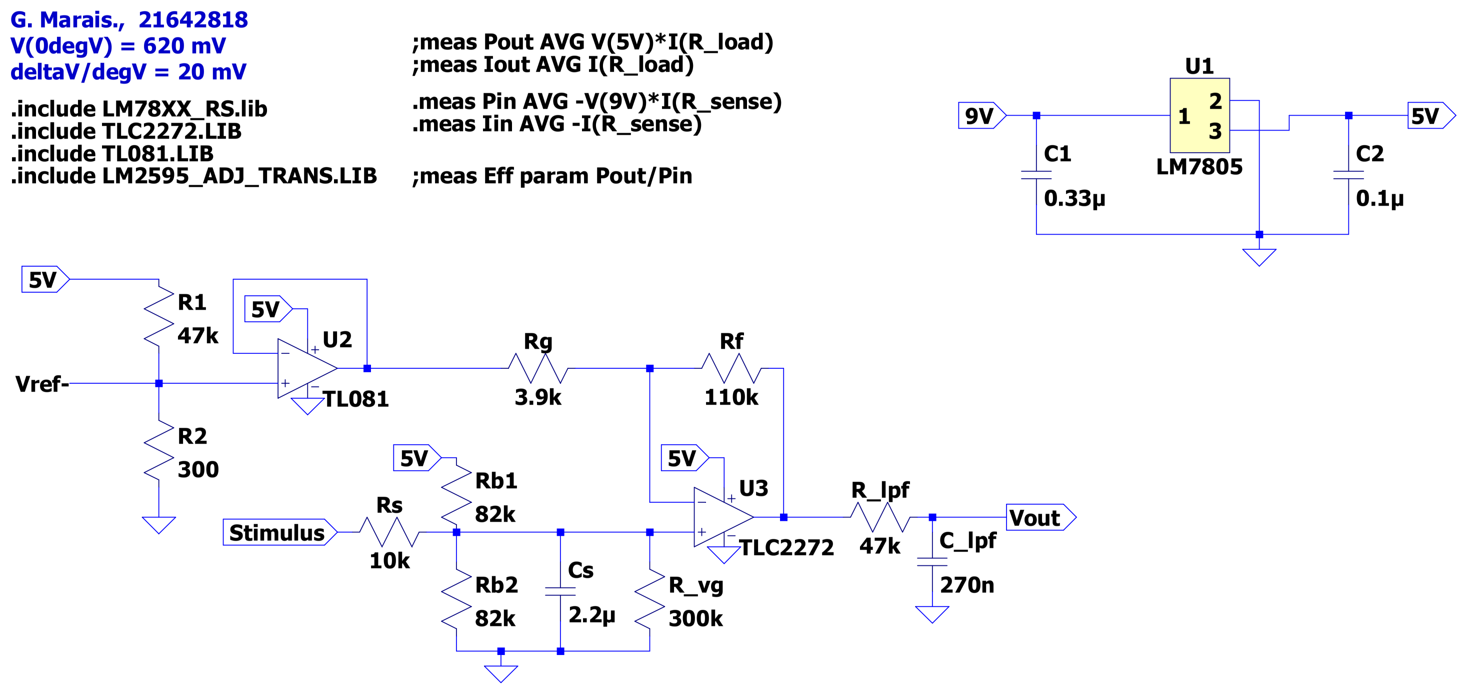


Figure C.1: Full Temperature Circuit Diagram

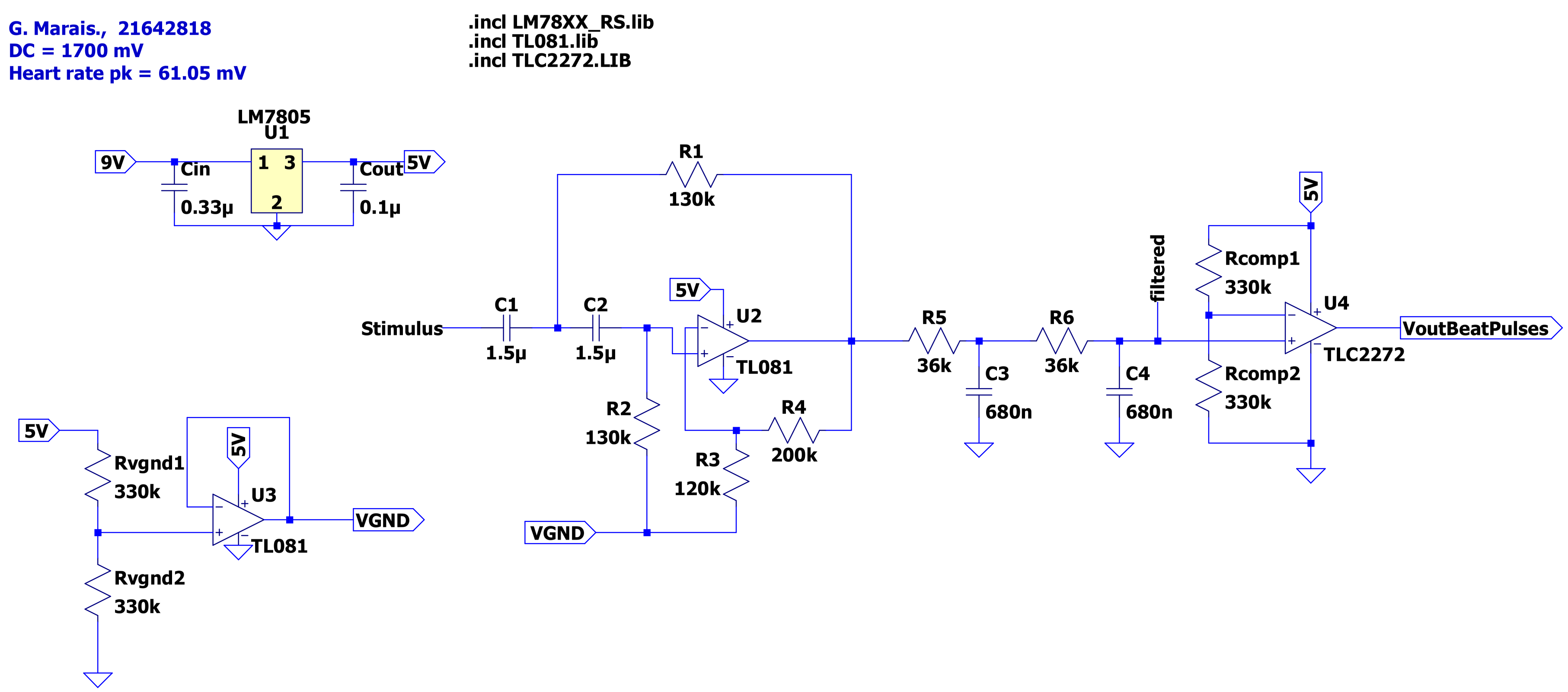


Figure C.2: Full Heartbeat Circuit Diagram