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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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ES Cishugi Voorletters en van / *Initials and surname*	September 25, 2020 Datum / *Date*

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Nomenclature

Variables and functions

V^+	Operational amplifier non-inverting input
V^-	Operational amplifier inverting input
VIN_max	Operational amplifier maximum input voltage
VIN_min	Operational amplifier minimum input voltage
VIN_diff	Operational amplifier differential input voltage

Acronyms and abbreviations

Op Amp	Operational Amplifier
LPF	Low-pass Filter
HPF	High-pass Filter
FFT	Fast Fourier Transform

Chapter 1

System design

1.1. System overview and rationale

In this project, a health monitoring system comprising an analogue temperature sensor(developed and design in Assignment 1 [1]) and an optic heart rate monitor are implemented. For this report, the implementation and design of the heart rate monitor are covered. We wish to measure the user's heartbeats via an optical heart rate sensor and process the signal such that it can be further analysed with a microcontroller. This process requires first, filtering noise out of the heartbeats signal and applying a gain using both a Low-pass and a High-pass filter. The filtered signal is then fed into a Schmidtt trigger, which is a comparator circuit with both a high and low threshold voltages allowing to output square waves. However, the comparator output pulses have varying durations; Hence, a D-type flip-flop, in a monostable or one-shot configuration is used to normalise the pulses duration to about 200ms. In addition, a transducer is used to convert a given heart rate to a specific analog value. The transducer circuit comprises a LPF allowing different attenuations to the heartbeat signals depending on their frequencies(rate), a level shifting differential amplifier and a peak detector circuit.
The full temperature sensor conditioning circuit drew 10.77mA [1]. Hence, the remaining current margin is 89,23mA which has to be limited to bellow 25mA for this part of the project. Large resistor values and power sensitive designs will therefore be used to ensure that we adhere to this requirement. Figure 1.1 bellow illustrates the system design.

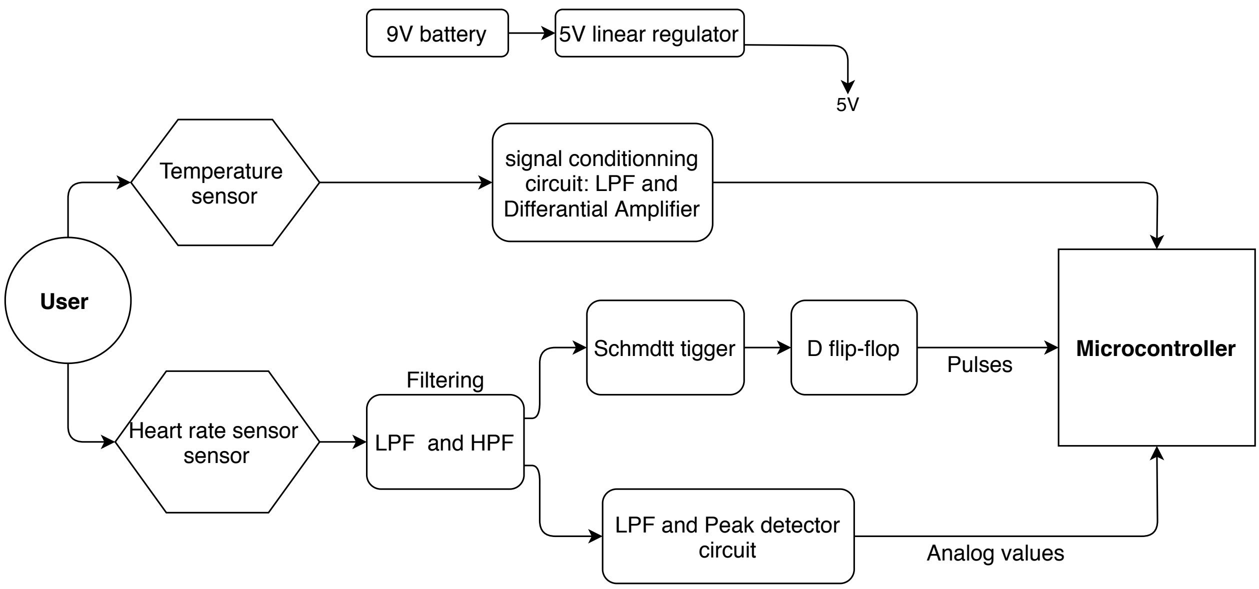


Figure 1.1: System diagram

Chapter 2

Heart rate sensor

2.1. Introduction

This section deals with the design of the **heart rate sensor conditioning** circuit(with a filtering and thresholding modules) as well as a **transducer**.

2.2. Design

2.2.1. Filtering

To design the appropriate filters, the FFT of the heartbeat signals(50bpm, 90bpm and 150bpm) were analysed. The analysis results were recorded in table 2.1 bellow.

Heart rate	main frequency component	Harmonics	*low frequency components*	*high frequency components*
50bpm	0.833Hz	at 1.66 and 2,49Hz	between 0.2 and 0.3Hz	at 20, 50 and 60Hz and more
90bpm	1.5Hz	at 3 and 4.5Hz	between 0.2 and 0.3Hz	at 20, 50 and 60Hz and more
150bpm	2.4Hz	at 5 and 7.5Hz	between 0.2 and 0.3Hz	at 20, 50 and 60Hz and more

Table 2.1: Heartbeat signals frequency components from FFT analysis

From the above results, we can observe that unlike the main frequency components and harmonics, which are specific to each heart rate, the low and high frequency components are common to all signals. Additionally, in the time domain, the heartbeat signals have a sinusoidal variation in amplitude of frequency approximately 0.25Hz. Therefore, we can conclude that high frequency components correspond to the superimposed noise while the low frequency components are responsible for the sinusoidal amplitude variations. Hence, the useful frequency components are between 833mHz and 8Hz.

- **Low-pass filter design:** Figure 2.1 bellow illustrates the LPF design.

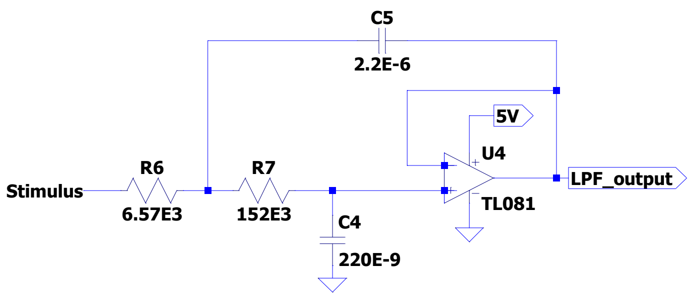


Figure 2.1: LPF circuit diagram

To suppress the high frequency noise, a second order active LPF is used with a corner frequency of 8Hz.
Resistors and capacitors values were computed using the formula: $f_C = \frac{1}{2\pi\sqrt{R_6 R_7 C_4 C_5}}$. The circuit has initially four unknowns. R7, C4 and C5 were picked as: $R7 = 152\,k\Omega$, $C4 = 220\,nF$ and $C5 = 10 \cdot C4 = 2.2\,\mu F$
$\therefore 8 = \frac{1}{2\pi\sqrt{R_6 \cdot 152\,k\Omega \cdot 220\,nF \cdot 2.2\,\mu F}}$, $\therefore R6 = 6.57\,k\Omega$.
• **High-pass filter design:** To suppress the sinusoidal amplitude variation, a second order active HPF is used with a corner frequency of 0,6Hz. Additionally, given that the heartbeat signals are 61.05mVp(without noise), a gain of 20V/V is introduced in the HPF bringing the amplitude to about 1.22Vp to facilitate thresholding. Figure 2.2 bellow illustrates the HPF design.

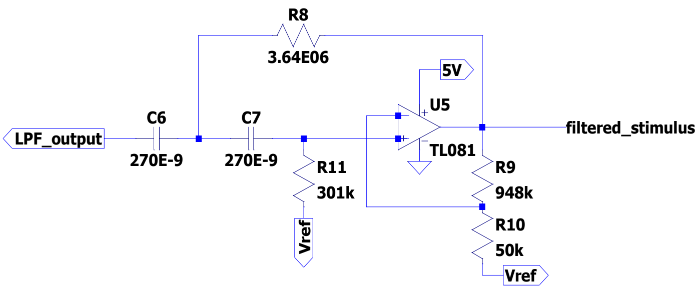


Figure 2.2: HPF circuit diagram

To get R9 and R10 values, the gain equation: $\text{Gain}(Av) = 1 + \frac{R9}{R10}$ is used.
We pick $R10 = 50\,k\Omega$
$\therefore 20 = 1 + \frac{R9}{50\,k\Omega}$; $\therefore R9 = 948\,k\Omega$
Similar to the LPF, to get C6, C7, R8 and R11 values, the formula: $f_C = \frac{1}{2\pi\sqrt{R_8 R_{11} C_6 C_7}}$ is used.
R11, C6 and C7 were picked as: $R11 = 301\,k\Omega$, $C6 = 270\,nF$ and $C6 = C7 = 270\,nF$.
$\therefore 0.6 = \frac{1}{2\pi\sqrt{R_8 \cdot 301\,k\Omega \cdot 270\,nF \cdot 270\,nF}}$, $\therefore R8 = 3.64\,M\Omega$.
To prevent the Op Amp from going into negative saturation, a virtual ground of 2,5V designed with a voltage divider form the 5V regulator output is used. This is labelled is Vref in the above circuit diagram.
In both the LPF and HPF circuits, the Op Amp used is the TL081. In the two cases, the minimum and maximum input voltages(VIN_min and VIN_max) to the Op Amp are both between 1.78 and 2.10; same thing for the differential(VIN_diff) and common-mode input voltages. These values, falls well within the maximum ratings of the TL081 Op Amp [2].

2.2.2. Thresholding

Thresholding happens in two steps: first using a Schimidt trigger to output square waves then the duration of the pulses is normalised to 200ms using a D flip-flop.
•**Schimdt trigger:** To develop appropriate thresholding, the filtered heart beat signals amplitude were analysed in the time domain while considering the allowable spec deviations. Table 2.2 records the analysis results:

Heart rate	DC-offset	min voltage	max voltage	range with spec deviation considered (+- 0.2Vdc and 10% noise)
60bpm	2.5V	1.8	3.4	1.6 to 3.6
150bpm	2.5V	1.65	3.4	1.45 to 3.6

Table 2.2: Thresholding

Hence, we can use 2.3V and 2.7V as low and high threshold voltages (V_{Th_low} and V_{Th_high}) respectively to detect all beats even with the specs deviations. Figure 2.3 bellow illustrates the Schmidt trigger design.

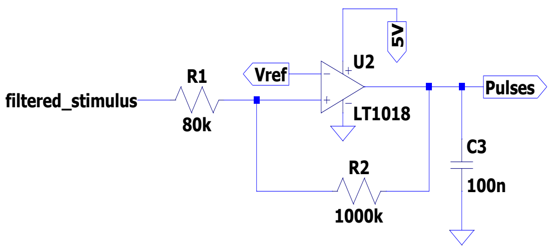


Figure 2.3: Schmidtt circuit diagram

R2 = 1 MΩ and R1 computed using the formula: $V_{in} = \frac{R_1}{R_2}\left(1 + \frac{R_2}{R_1}\right) \cdot V_{ref} - \frac{R_1}{R_2} \cdot V_{out}$
for $V_{in} = V_{Th\_high} = 2.7$, $V_{out} = 0V$
$\therefore 2.7 = \frac{R_1}{1000.60^3}\left(1 + \frac{1000.10^3}{R_1}\right) \cdot 2.5 - \frac{R_1}{1000.10^3} \cdot 0$
for $V_{in} = V_{Th\_low} = 2.3$, $V_{out} = 5V$
$\therefore 2.3 = \frac{R_1}{1000.60^3}\left(1 + \frac{1000.10^3}{R_1}\right) \cdot 2.5 - \frac{R_1}{1000.10^3} \cdot 5$
$\therefore$ R2 = 80 kΩ, C3(100 nF)is added to reduce noise on the trigger output.
•One shot cicruit: Implemented with a D flip-flop and an R-C network. Figure 2.4 bellow illustrates design.

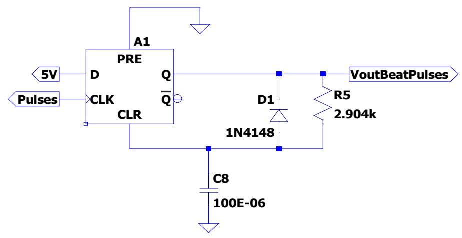
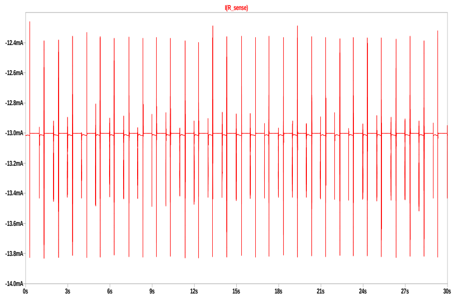


Figure 2.4: One-shot circuit diagram

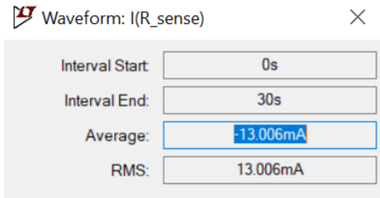
The RC network is design to achieve a 200ms pulse duration. C8 was picked as C8 = 100 µF and R5 computed using the formula: $R = -\frac{t}{C \cdot \ln(1 - V_{cap}/V_{final})} = -\frac{0{,}2}{100 \cdot 10^{-6} \cdot \ln\left(1 - \frac{2{,}489}{5}\right)} = 2.904\,k\Omega$
In the Comparator circuit, the Op Amp used is the LT1018. The minimum and maximum input voltages(VIN_min and VIN_max) to the Op Amp are both between 1.6 and 3.6; same thing for the differential(VIN_diff) and common-mode input voltages. These values, falls well within the maximum ratings of the LT1018 Op Amp [4].
Transducer: The transducer was designed with a second order LPF with corner frequency 0.65Hz, a level shifting differential amplifier and a peak detector circuit. See Appendix C, figure C.1 for the circuit diagram and full design.

2.3. Results

•**Power supply:** figure 2.5 bellow illustrates the total current drawn.



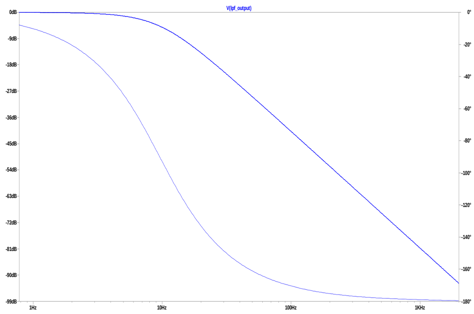
(a) total current drawn plot



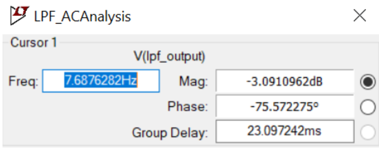
(b) Average value

Figure 2.5: Total current drawn

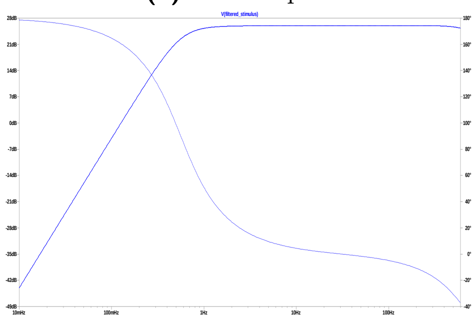
•**Filters frequency response:** figures 2.6 bellow illustrates frequency responses of the LPF and HPF.



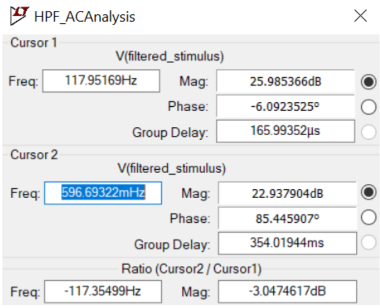
(a) LPF fft plot



(b) LPF corner frequency



(c) HPF fft plot



(d) HPF corner frequency

Figure 2.6: LPF and HPF frequency response

•**Conditioning:** table 2.3 records the measured input and output ranges for 60bpm, 120bpm and 150bpm heartbeat signals. The screen-grabs of the spice simulations can be found in Appendix C in figure C.2.

Heart rate	input range	output range
60bpm	low:1.817 ;high:2.02	low: 0; high: 5V
120bpm	low:1.799 ;high:2.00	low: 0; high: 5V
150bpm	low:1.789 ;high:2.01	low: 0; high: 5V

Table 2.3: Input and output range measurements

•**Thresholding:** table 2.4 below records the measured high and low threshold voltages for a 60bpm and 150bpm heartbeat signals. The screen-grabs of the spice simulations can be found in Appendix C in figure C.3.

Heart rate	measured low threshold	measured high threshold	*Designed thresholds*
60bpm	2.356V	2.70V	low: 2.3V
150bpm	2.282V	2.769	high: 2.7V

Table 2.4: thresholding measurements

•**Pulses duration:** table 2.5 below records the measured output pulses duration for a 60bpm and 150bpm heartbeat signals. The screen-grabs of the spice simulations can be found in Appendix C in figure C.4.

Heart rate	measured output pulse duration
60bpm	196.1655ms
150bpm	187.8953ms

Table 2.5: Output pulses duration

•**Transducer:** table 3.1 records the measured range and settling time of the transducer. The screen-grabs of the spice simulations can be found in Appendix C in figure C.5.

Heart rate	Transducer or analog output	Settling time
50bpm	0.7855V	318ms
150bpm	4.6851V	655ms
achieved output range:	4.6851 - 0.7855 = 3.8996V	

Table 2.6: Transducer output range and settling time

2.4. Summary

From the above simulations results:
•The total current drawn is averaged at 13.00mA(smaller than the remaining 89.23mA [1] regulator current available and the 15mA current requirement)
•The two filters had satisfactory performances: the measured the LPF corner frequency was 7.69Hz(designed for 8Hz) while the measured HPF corner frequency was 0.597Hz and a 25.96dB gain(designed for 0.6Hz and 26.02dB).
•The full heart rate sensor minimum to maximum output ranges from 0 to 5V while the input ranges from 1.817 to 2.02V.
•The measured low threshold, considering the allowable spec deviations varies between 2.82 and 2.356V (designed $V_{Th\_low} = 2{,}3V$) while the high threshold varies between 2.70 and 2.79 (designed $V_{Th\_high} = 2{,}7V$)
•The measured output pulses duration varies between 187.895ms(for 150bpm) and 196.166ms(for 60bpm), close to the 200ms design value and grater than the 150ms requirement.
•The measured transducer output range is 3.8995V and an average settling time smaller than 1s. All these values meet the necessary requirements.

Chapter 3

System and conclusion

3.1. System

The heart rate sensor circuit will be connected to a microcontroller. While the output pulses are best suited toward the microcontroller DAC input, the analog transducer outputs are designed for the microcontroller ADC input. The acquired analog data will be used by the microcotroller to estimate the heart rate using a calibration constant computed using the measured transducer output for various heartbeats signals as recorded in table 3.1 below:

Heart rate	**Transducer analog output: $\mathbf{V_{out}}$**
50bpm	0.7855V
70bpm	0.8843V
90bpm	1.8718V
110bpm	2.4745V
130bpm	3.9387V
150bpm	4.6851V

Table 3.1: Transducer analog output

Using the above data in Excel, we get the calibration formula:
Heartrate[in bpm] = 65,067 . $(\mathbf{V_{out}})^{\mathbf{0,5354}}$

Additionally, the remaining current for the rest of the circuit can be calculated as:
$I_{\text{remain}} = I_{\text{available}} - I_{\text{sense}}$
$I_{\text{available}} = 89.23\text{mA}$ [1].
$I_{\text{sense}} = 13.00\text{mA}$, see figure 2.5 in the previous section.
$\therefore\ I_{\text{remain}} = 89.23 - 13.00 = 76.23\text{mA}$.

3.2. Lessons learnt

•There are various ways to design a circuit given its requirements: for instance, in the transducer, while complex circuits and specialised components are advisable for such task, a simple a LPF and a peak detector were used and the given requirements were met.
•I improved my LATEX skills
•The earlier you start to work an a certain task, the more you enjoy doing it.

Bibliography

[1] E. S. Cishugi, *E344 Assignment 1 Report*, Linear Voltage regulation and Temperature sensor conditioning circuit design report, August 2020.

[2] *General purpose JFET single operational amplifiers*, TL081 datasheet, ST Microcontroller, June 2008.

[3] *TLC227x, TLC227xA: Advanced LinCMOS Rail-to-Rail Operational Amplifiers*, TLC2272 datasheet, Texas Instruments, March 2016.

[4] *LT1017/LT1018, Micropower Dual Comparator*, LT1018 datasheet, Linear Technology, 2005.

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, Elijah Seth Cishugi 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.

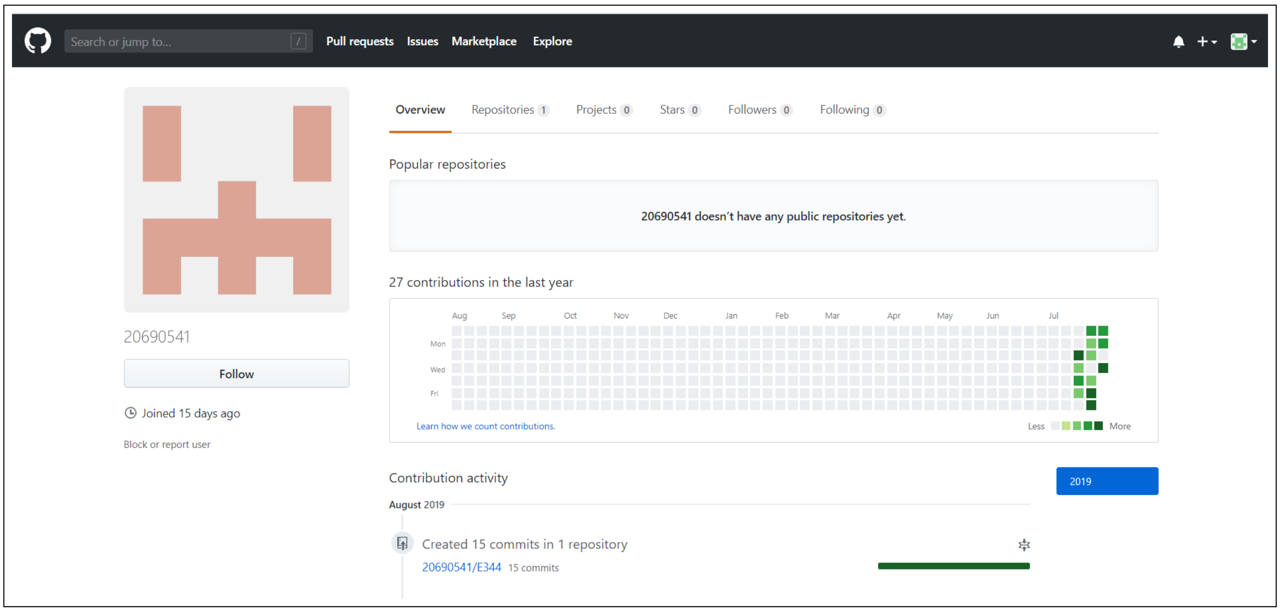
I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing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

Signature: .... Date: 16th / August / 2020

1

Appendix B

GitHub Activity Heatmap



Appendix C

Additional Circuit diagrams and Spice simulation results

1.Transducer circuit diagram:

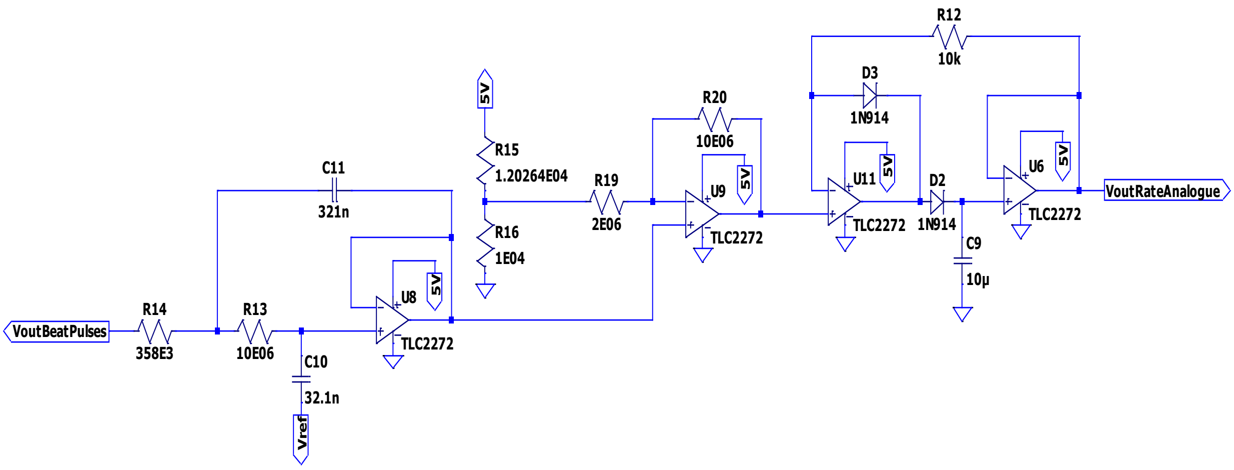


Figure C.1: Transducer circuit diagram

•LPF:

a LPF with corner frequency 0.65Hz is used to allow different attenuations to the pulses depending on the frequency.

Resistors and capacitors values were computed using the formula: $f_C = \frac{1}{2\pi\sqrt{R_{13}R_{14}C_{10}C_{11}}}$. The circuit has initially four unknowns. R13, C10 and C11 were picked as: $R13 = 10\,M\Omega$, $C10 = 32.1\,nF$ and $C11 = 10 \cdot C10 = 321\,nF$

$\therefore 0.65 = \frac{1}{2\pi\sqrt{R_{14} \cdot 10\,M\Omega \cdot 32.1\,nF \cdot 321\,nF}}$, $\therefore R14 = 358\,k\Omega$.

•Level shifting differential amplifier: Designed for a gain $A_v = 6$ and a 2.7V DC offset.

$A_v = 1 + \frac{R_{20}}{R_{19}}$, we pick $R20 = 10\,M\Omega$

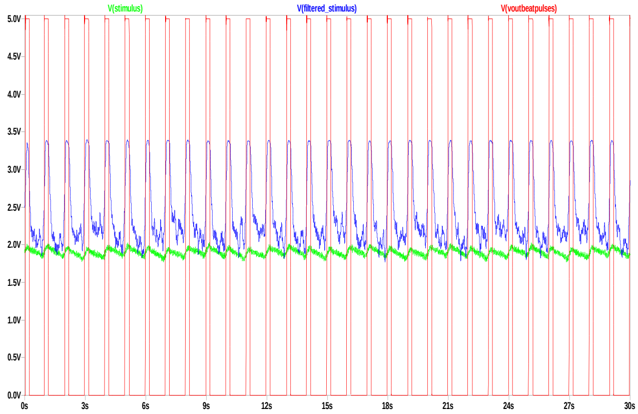
$\therefore R10 = 2\,M\Omega$

$V_{off\_set} = \frac{R_{16}}{R_{16}+R_{15}} \cdot 5$; We pick $R16 = 10\,k\Omega$

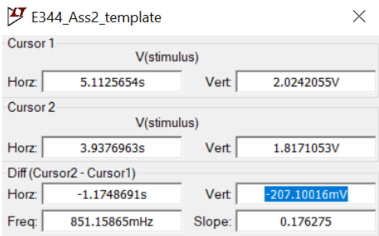
$\therefore R15 = 12.0264\,k\Omega$

•Peak detector: The configuration with two diodes and two Op Amp with a feedback resistor R12, was chosen to minimise noise and suppress any ripple at the transducer output. In the transducer circuit, the Op Amp used is the TLC2272. The minimum and maximum input voltages(VIN_min and VIN_max) to the Op Amp are both between 0 and 4.8; same thing for the differential(VIN_diff) and common-mode input voltages. These values, falls well within the maximum ratings of the LT2272 Op Amp [3].

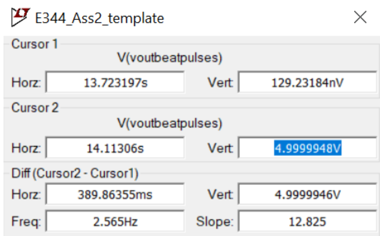
2.Input and output range measurements:



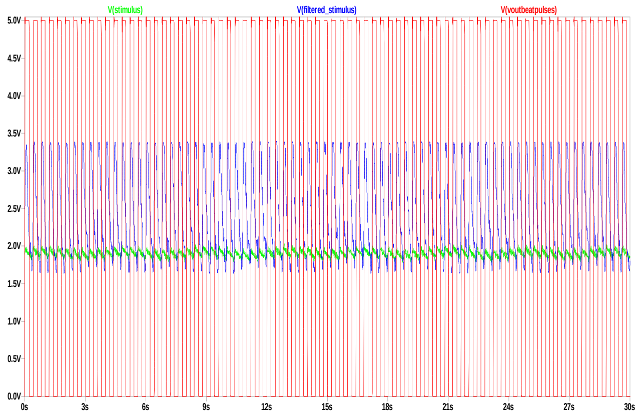
(a) 60bpm



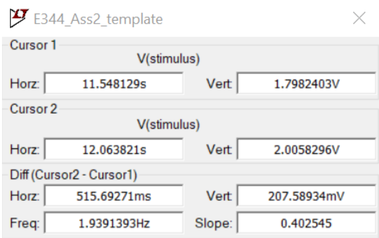
(b) 60bpm input range



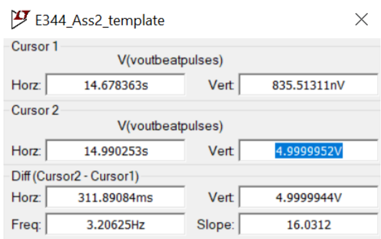
(c) 60bpm output range



(d) 150bpm



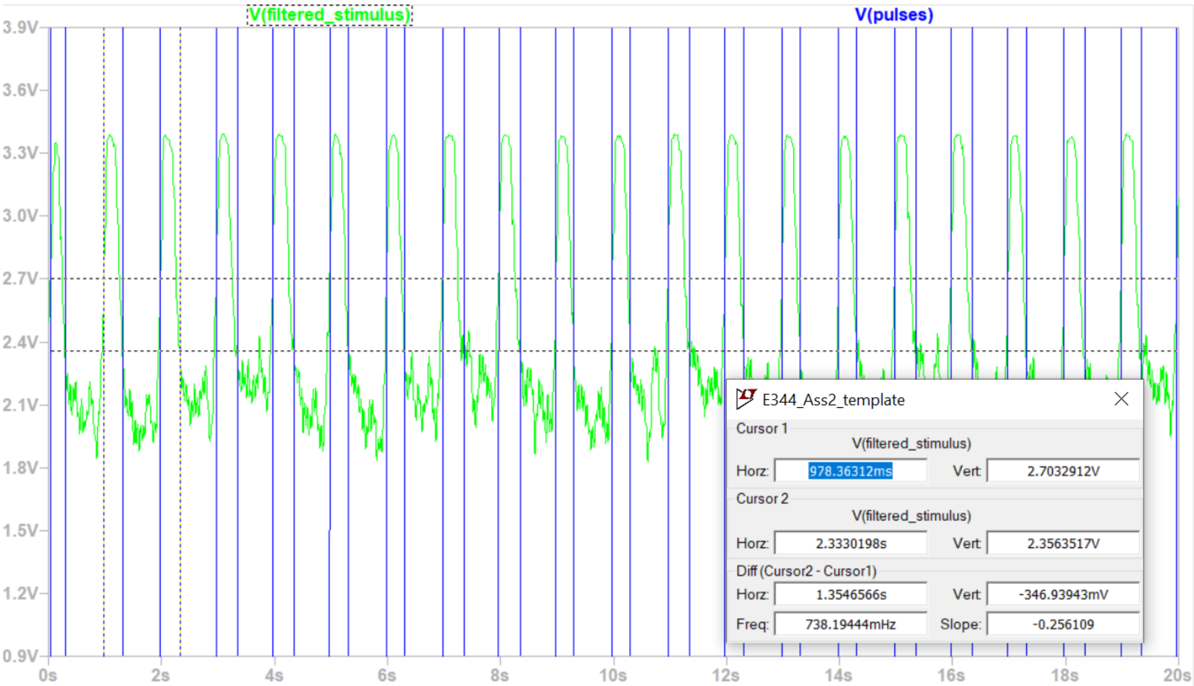
(e) 60bpm input range



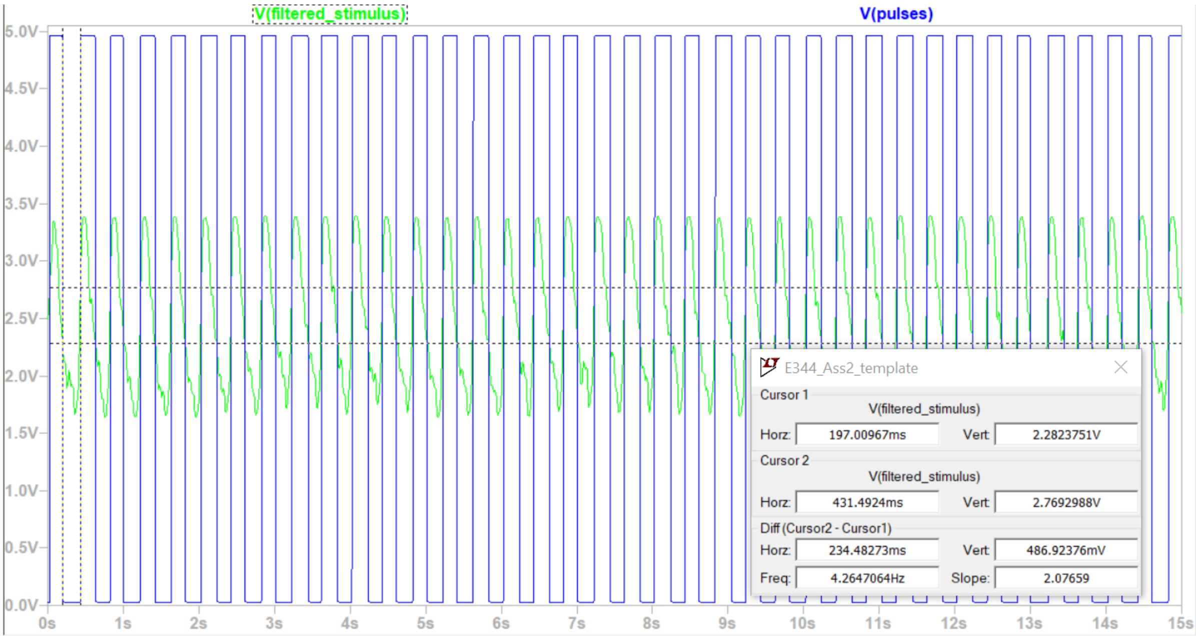
(f) 60bpm output range

Figure C.2: Input and Output ranges measurements

3. Thresholding measurements:



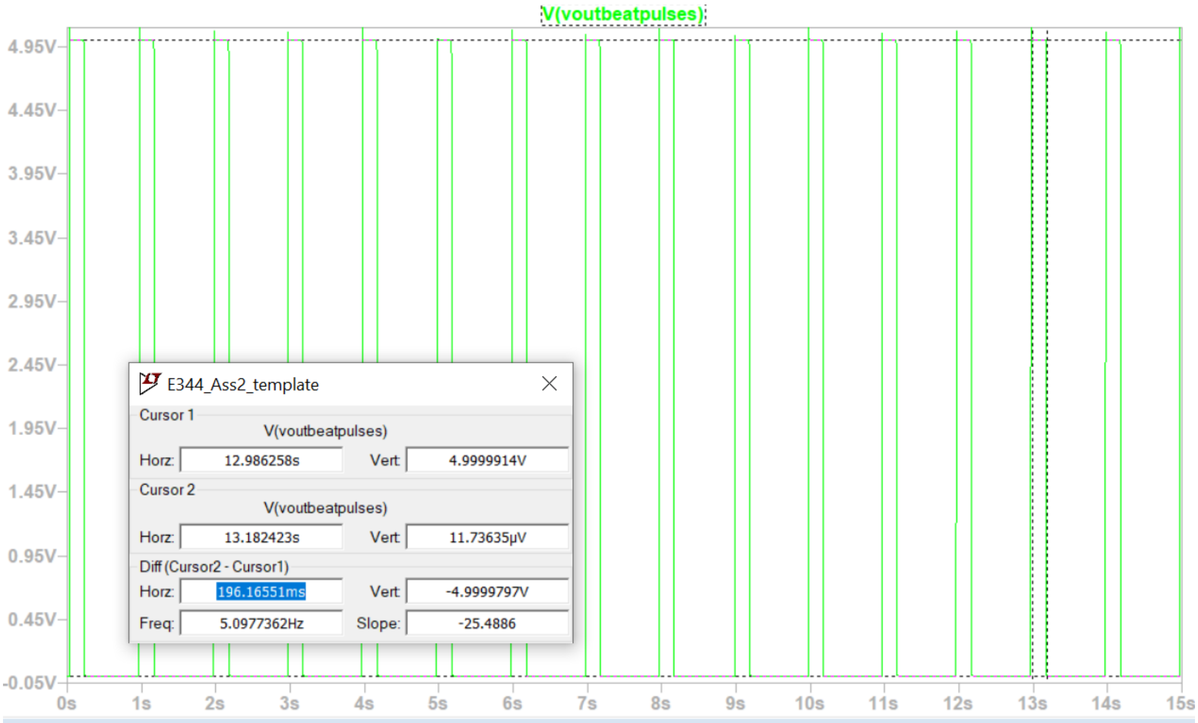
(a) 60bpm: cursor1 = measured high threshold, cursor 2 = measured low threshold



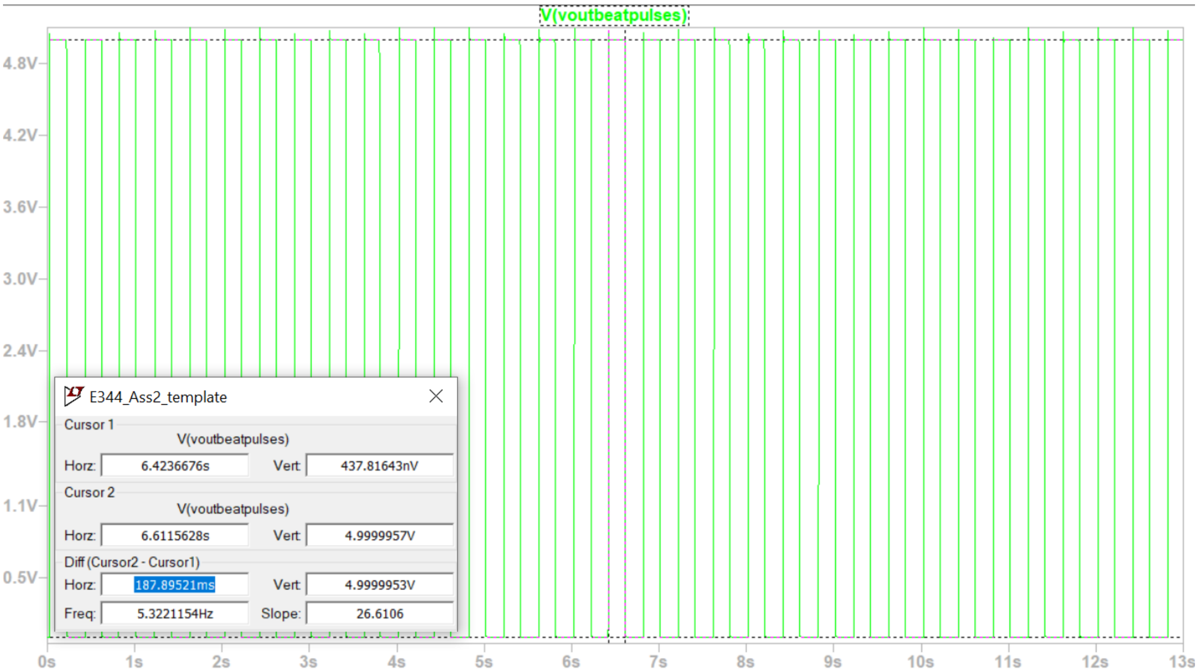
(b) 150bpm: cursor2 = measured high threshold, cursor 1 = measured low threshold

Figure C.3: Thresholding measurements

4.Pulses duration measurements:



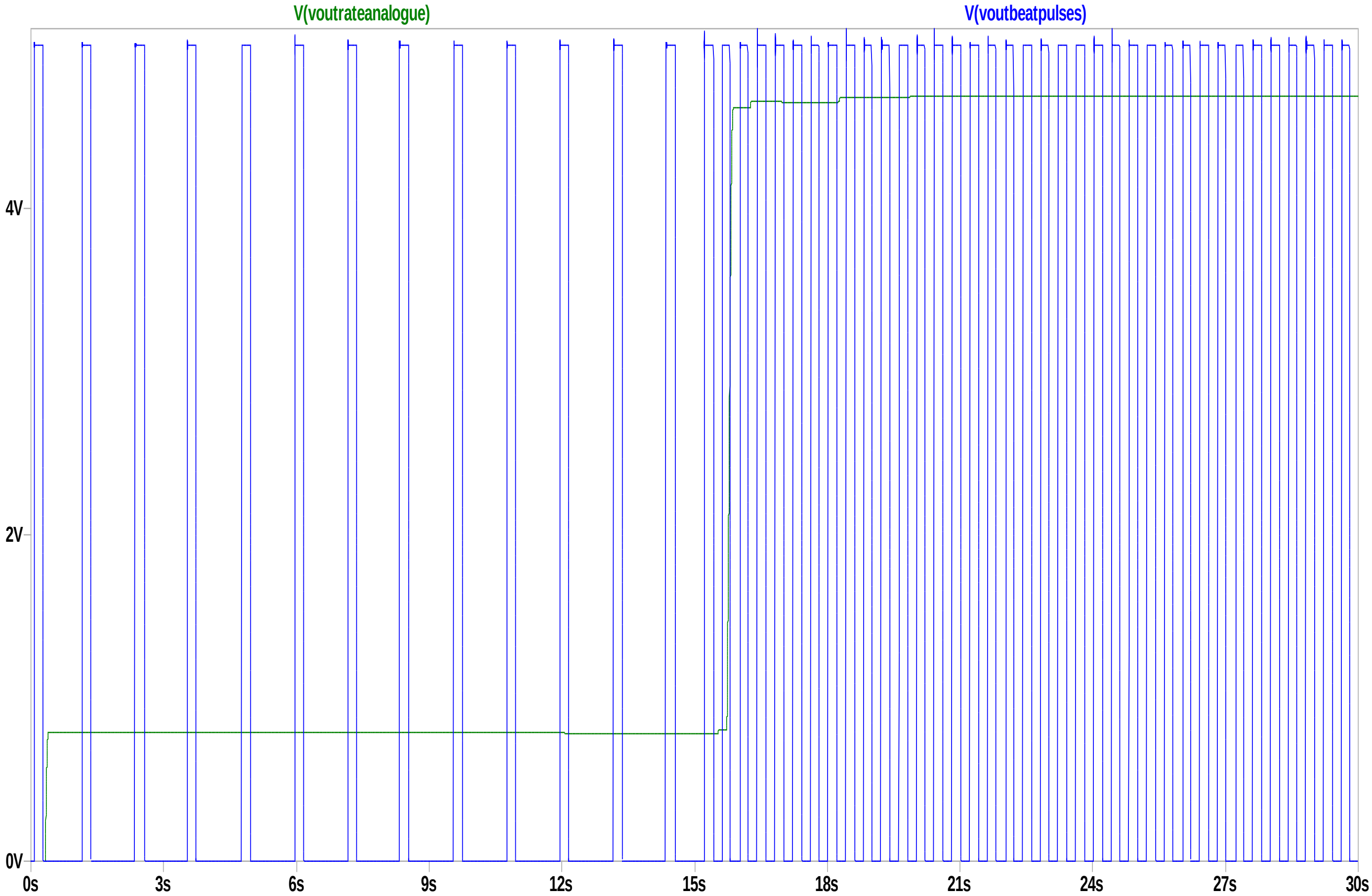
(a) 60bpm



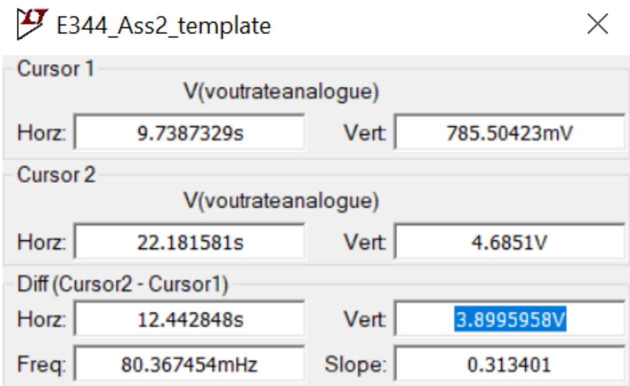
(b) 150bpm

Figure C.4: Pulses duration measurements

5.Transducer output range and settling time:



(a) 50bpm analog output: 0.7855V, settling time: 318ms; **150bpm** analog output: 4.6851V settling time: 655ms



(b) cursor reading

Figure C.5: Transducer output measurements