Bangladesh University of Engineering and Technology

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Project Report
PSpice-Driven Heart Signal Analysis

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Project Title:

PSpice-Driven Heart Signal Analysis

Abstract

The project aims to create a functioning and accurate Heart Signal Analysis Circuit through software-based simulation, using Pspice, and find the BPM of patients from ECG data. Subsequent amplification, integration, multiplication, and filtering techniques are applied to obtain a digital signal from which the Pulse Rate is extracted. The heart Rate Monitor Circuit is a crucial component in biomedical instrumentation and health tracking systems.

Objectives

- To design and simulate a Heart Signal Analysis Circuit that can accurately interpret and analyze heart rate data and obtain the BPM of a patient.
- To understand the functionality and working of each component in the circuit. Such as instrumentation amplifiers, notch filters, integrators, inverting amplifiers, multipliers, and comparators
- Accurately detect and count the peaks corresponding to heartbeats.
- To understand the principles of biomedical instrumentation and signal processing.
- To learn and apply the simulation tools in a real-world application.

Introduction

The human heart, with its rhythmic beats, has been an emblem of life and vitality throughout history. Heart rate is the number of times our heart beats per minute. It is measured in beats per minute (BPM). The normal resting heart rate for adults is between 60 to 100 BPM. However, it can vary depending on a number of factors, such as age, fitness level, and activity level.

At its core, the Heart Signal Analysis Circuit works by detecting the electrical impulses generated by the heart. These impulses, commonly referred to as the Electrocardiogram (ECG), manifest as waves, each corresponding to a specific part of the cardiac cycle. Our circuit amplifies these weak signals, filters out any noise or interference, and then processes them to display a readable heart rate as a digital signal.

Real-Life Applications

HEALTHCARE INDUSTRY: Heart rate monitor circuits are crucial in medical equipment like ECG machines, helping doctors monitor and diagnose cardiovascular conditions more effectively.

FITNESS INDUSTRY: Portable heart rate monitors integrated into smartwatches or fitness bands allow athletes and fitness enthusiasts to optimize their workouts based on real-time heart rate data.

RESEARCH: In academic and R&D settings, heart rate monitor circuits can be used in studies examining human physiology, stress, and the effects of various interventions on cardiac health.

PERSONAL USE: DIY heart rate monitor kits and readily available devices enable individuals to track their heart rate for personal wellness, potentially alerting them to irregularities that may require medical attention.

Software and Tools

PSPICE: CIRCUIT SIMULATION

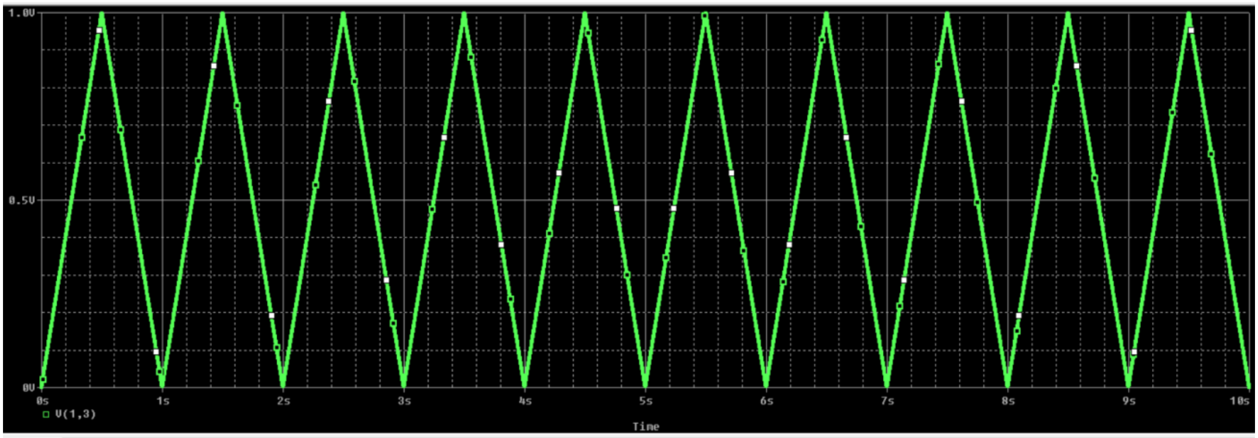
For the circuit design and simulation part of the project, Pspice was utilized. This powerful software tool allowed us to perform intricate analog simulations to test various circuit configurations. Pspice provided a virtual environment where we could validate the functionality of our monitoring circuit before proceeding to the hardware implementation stage. We conducted transient analysis to ensure that the circuit meets all necessary specifications for accurate heart rate (BPM).

Required Elements

1. Operational Amplifiers – uA741
2. Resistors
3. Voltage Source (Sine)
4. Voltage Source (Pulse)
5. Capacitors

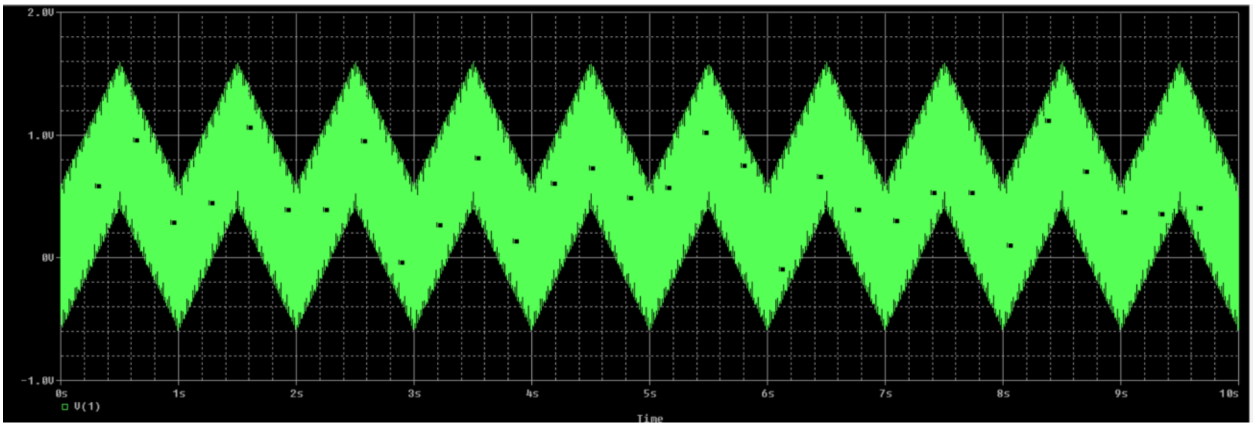
Heartbeat Signal and necessary modelling:

Since, it was not possible to give actual heart beat data as input in PSPICE, We modelled the heartbeat signal as a triangular waveform of 1V peak, 1Hz.



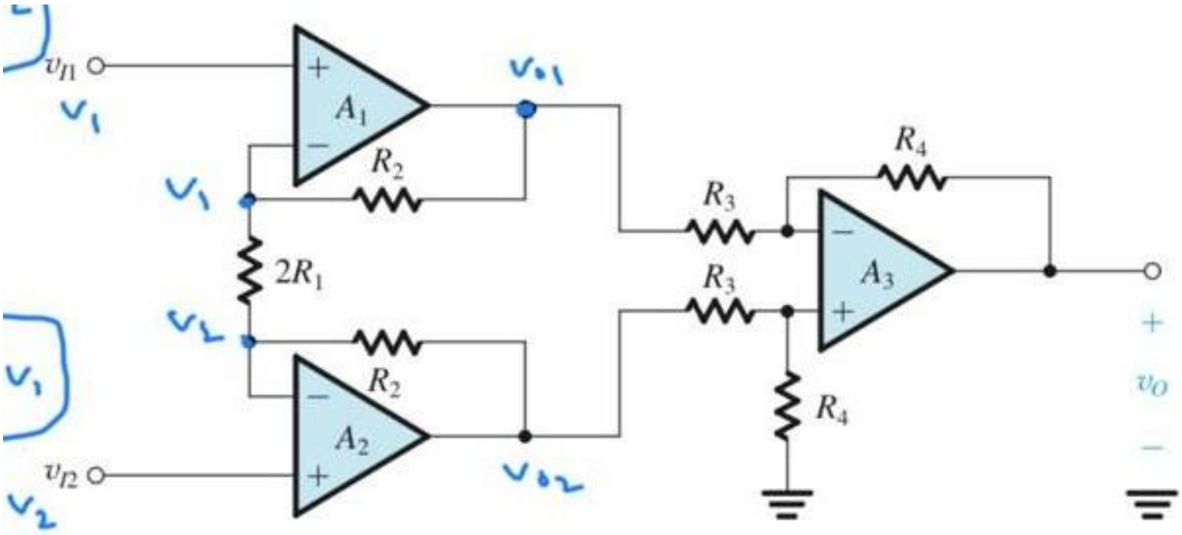
Next we mixed two noises with it using pspice voltage source in series.

1) 0.1V, 60Hz (power line noise)
2) 0.5V , 2kHz(High frequency noise)



The result was this waveform. We Designed a circuit that will filter out the noise and bring back the original signal.

INSTRUMENTATION AMPLIFIER:



(b)

An instrumentation amplifier is used to amplify very low-level signals, rejecting noise and interference signals. Examples can be heartbeats, blood pressure,temperature, earthquakes and so on.

An instrumentation amplifier is a type of differential amplifier that has been outfitted with input buffer amplifiers, which eliminate the need for input impedance matching and thus make the amplifier particularly suitable for use in measurement and test equipment. Additional characteristics include very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedance. The most commonly used instrumentation amplifier circuit is shown in the Figure

Nodal analysis at V1,

$$\frac{V1 - V2}{2R1} + \frac{V1 - Vo1}{R2} = 0$$

$$Vo1 \ = V1\left(1 + \frac{R2}{2R1}\right) - \frac{R2}{2R1}V2$$

Nodal Analysis at V2,

$$\frac{V2 - V1}{2R1} + \frac{V2 - Vo2}{R2} = 0$$

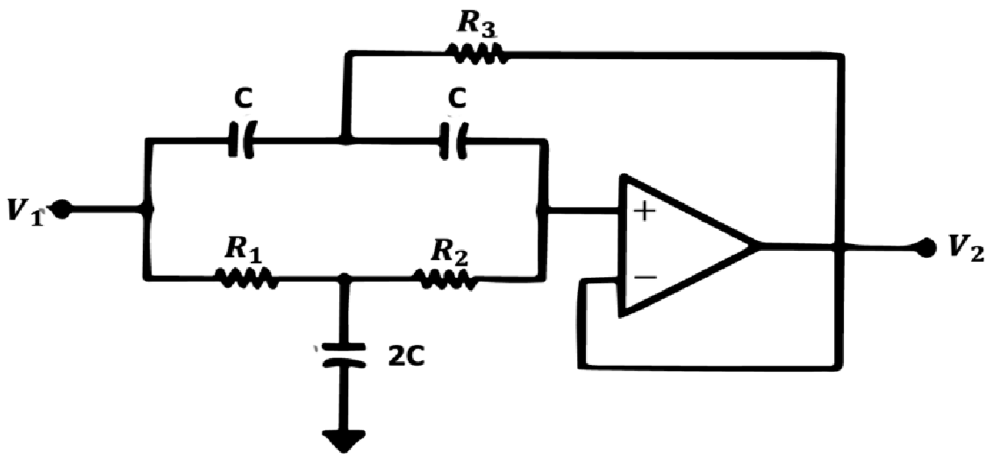
$$Vo1 \ = V2\left(1 + \frac{R2}{2R1}\right) - \frac{R2}{2R1}V1$$

$$Vo = \left(\frac{R4}{R3}\right)(Vo2 - Vo1)$$

$$Vo = \left(\frac{R4}{R3}\right)(1 + \frac{R2}{R1})(V2 - V1)$$

NOTCH FILTER:

A notch filter is a type of band-stop filter, which is a filter that attenuates frequencies within a specific range while passing all other frequencies unaltered. For a notch filter, this range of frequencies is very narrow. The notch filter is implemented by using twin T network. The attenuation frequency is given by $f_n = \frac{1}{2\pi RC}$



OP-AMP COMPARATOR:

A comparator circuit accepts input of linear voltages and provides a digital output that indicates when one input is less than or greater than the second. A basic comparator circuit can be represented in Figure3. The output is a digital signal that stays at a high voltage. level when the noninverting (+) input is greater than the voltage at the inverting () input and switches to a lower voltage level when the noninverting input voltage goes below the inverting input voltage.

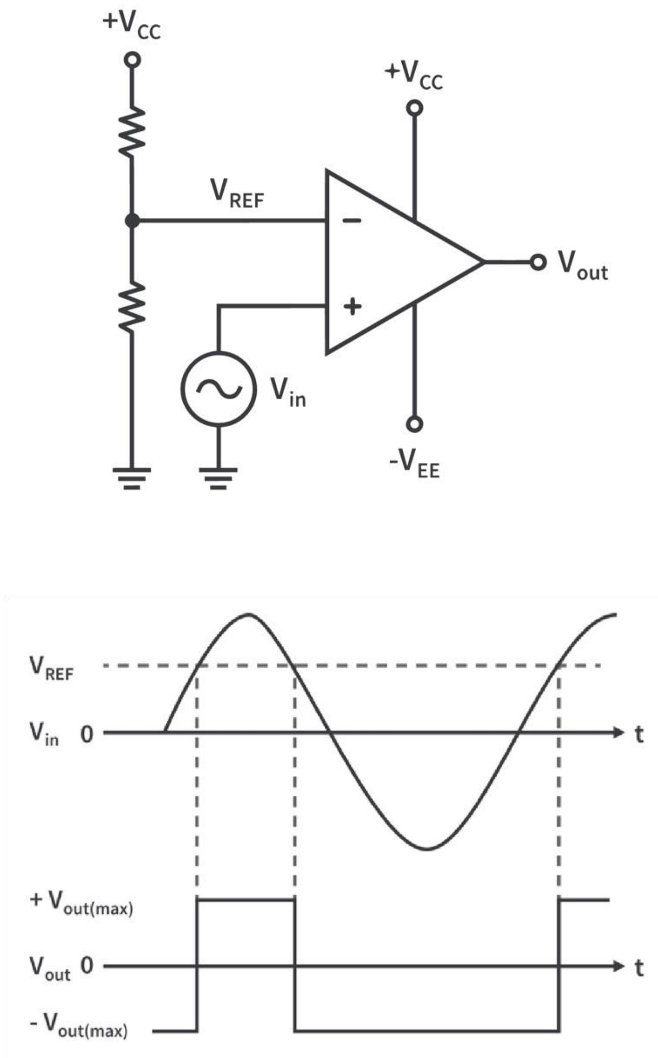
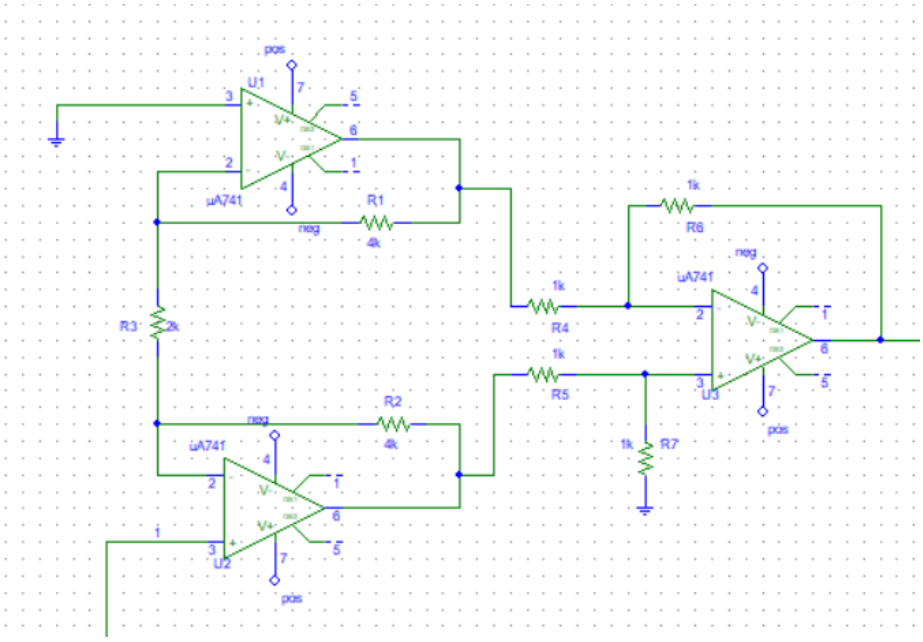


Figure 3 Op-amp Comparator

When $V_{in} > V_{ref}$, $V_o = +V_{CC}$

When $V_{in} < V_{ref}$, $V_o = -V_{EE}$

Instrumental Amplifier:

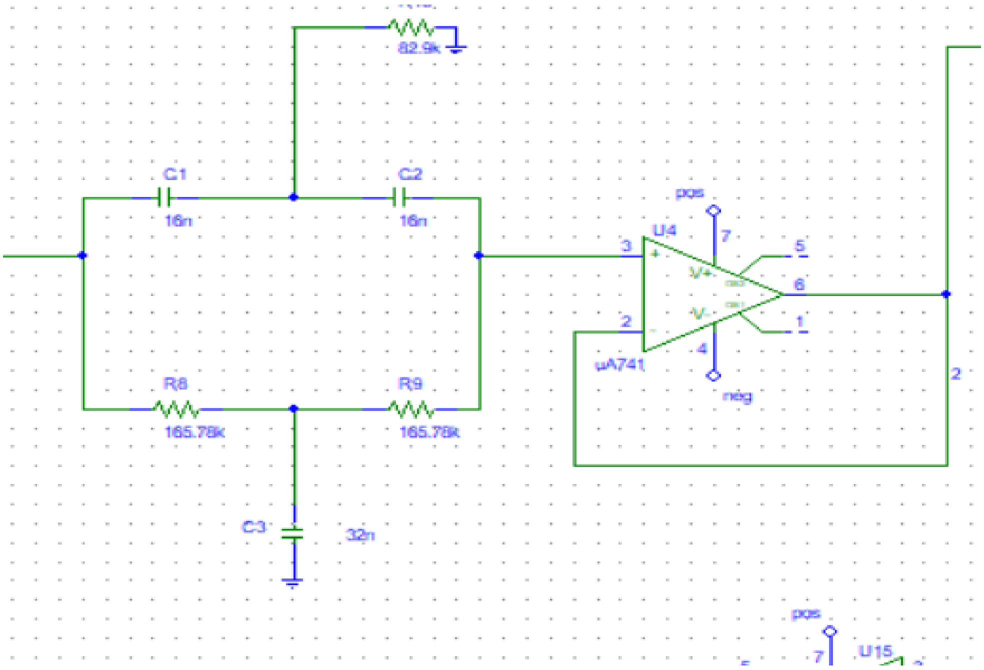


Calculation

$$Vo = \left(\frac{R4}{R3}\right)(1 + \frac{R2}{R1})(V2 - V1)$$

Here, V1 = 0V
We take gain = 5V/V.
R2 = 4k ohms, R1 = 1K ohms, R4 = R3 = 1k
Vo = 5V2(input)

NOTCH FILTER:



$$f_n = \frac{1}{2\pi RC}$$

The formula is used to calculate the notch frequency f_n of a filter, commonly used to eliminate or minimize a specific frequency component from a signal. In the case of 60 Hz power line interference, setting $f_n = 60$ Hz will help to eliminate that frequency from the signal.

C = C1 = C2 = 16nF

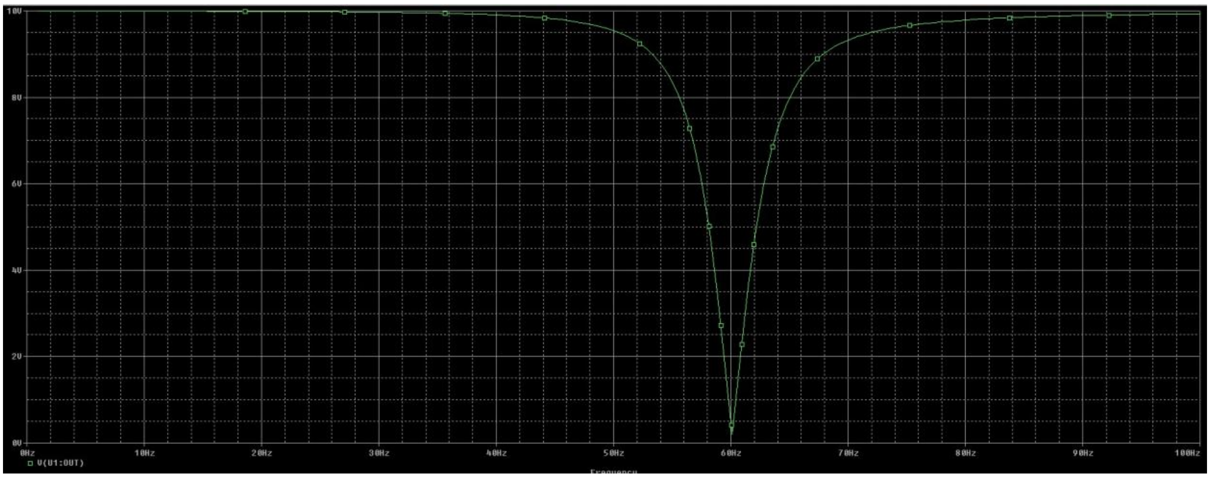
$$R = \frac{1}{2\pi * 60 * 16 * 10^{-9}} = 165.78k\ ohms$$

"

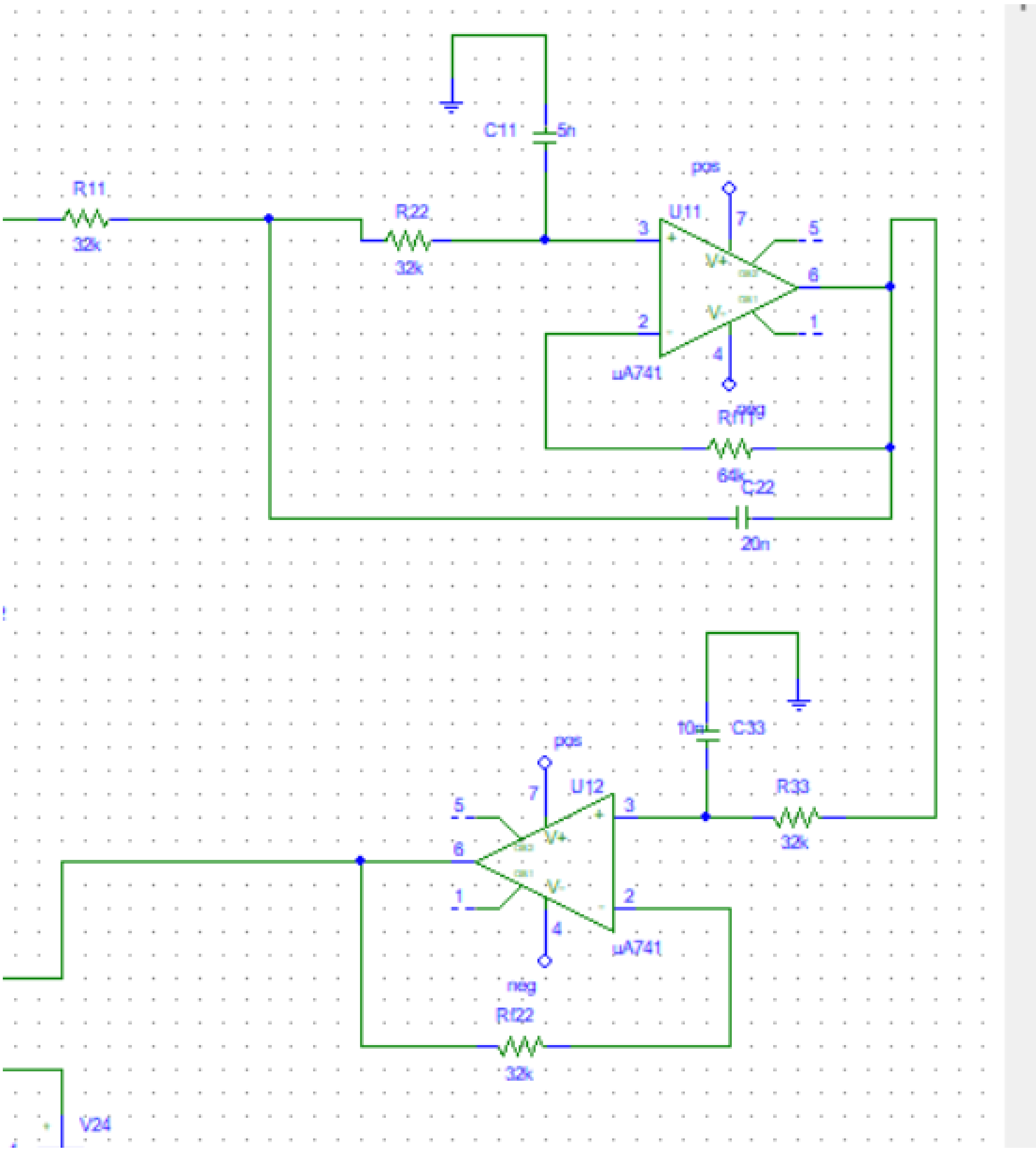
If $2C$ is desired, it would be:

$$\mathrm{C3} = 2C = 32\mathrm{nF}$$

This means that to notch out a 60 Hz frequency from your signal, you would use a resistor of 165.78 kilo ohms and a capacitor of 16nF in our filter circuit.



-60 dB/dec Low pass Butterworth Filter:



For a -60 db/dec low pass filter,

$C_{11} = C_{33}/2$, $C_{22} = 2C_{33}$

$R_{11} = R_{22} = R_{33} = R$

We make the low pass filter with a cutoff frequency 1.5kHz .

We know, $f_c = \frac{1}{2\pi \text{RC33}}$

$$R = \frac{1}{2\pi * 1.5 * 10^3 * \text{C33}} \quad [\text{ let } C_{33} = 10\text{nF}]$$

R = 32 kohms.

So, R11 = R22 = R33 = 32 kohms .

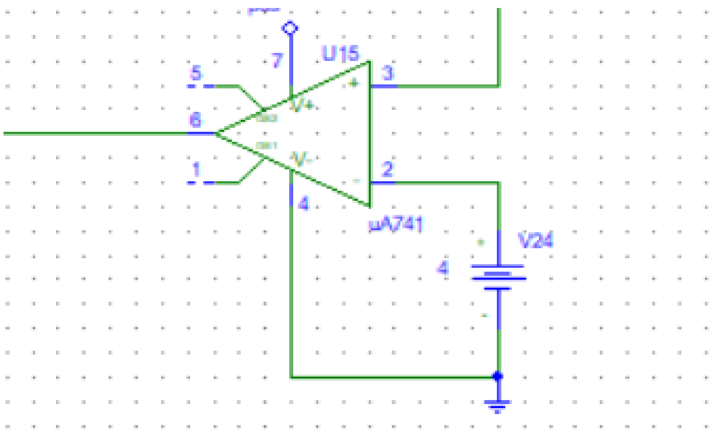
Then C_{11} = 10/2 = 5 nF .

Also C_{22} = 2* 10 = 20 nF .

And Rf_{11} = 2* R = 64 kohms.

Rf_{22} = R = 32 kohms.

OP-AMP COMPARATOR:

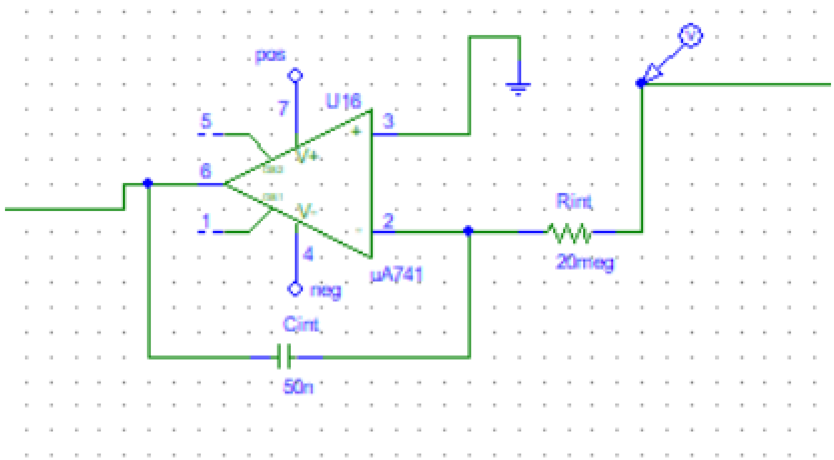


After filtering out all the noise we convert the triangular wave to digital pulse signal using op amp comparator. Our output peak is 5V. When the signal is higher than 4V we consider it to be a beat. It is represented at pulse peak

$V_{\text{ref}} = 4\text{V}$

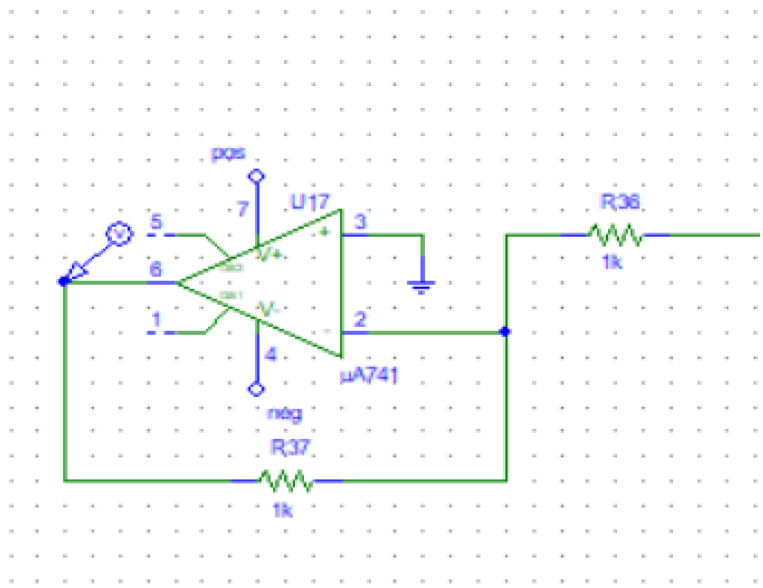
We convert the total output to +Vsat($+20v$) to $-V_{\text{sat}}$ ($0 \quad V$) according to V ref.

INTEGRATOR:



We set the gain of integrator 1/RC = 1 i.e. RC = 1
C = 50 nF
R = 1/C = 20 Mega Ohms

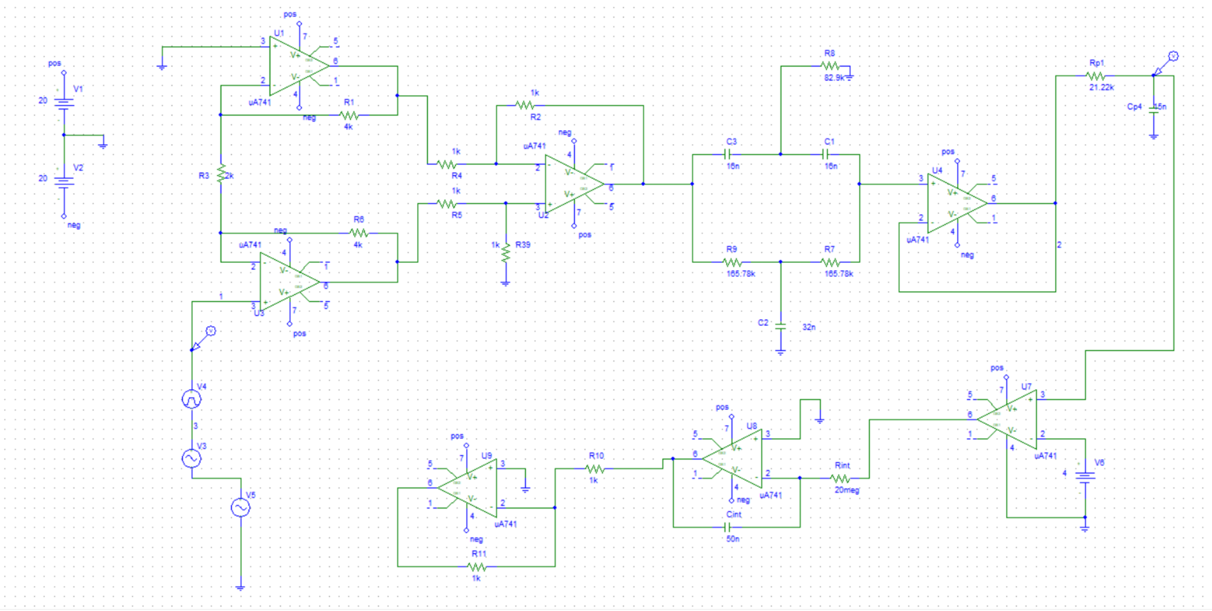
INVERTING OPERATIONAL AMPLIFIER



We take Rf = Ri = 1k to use it as a unity gain inverting amplifier.

Full Circuit:

Part A: With Passive Filters:

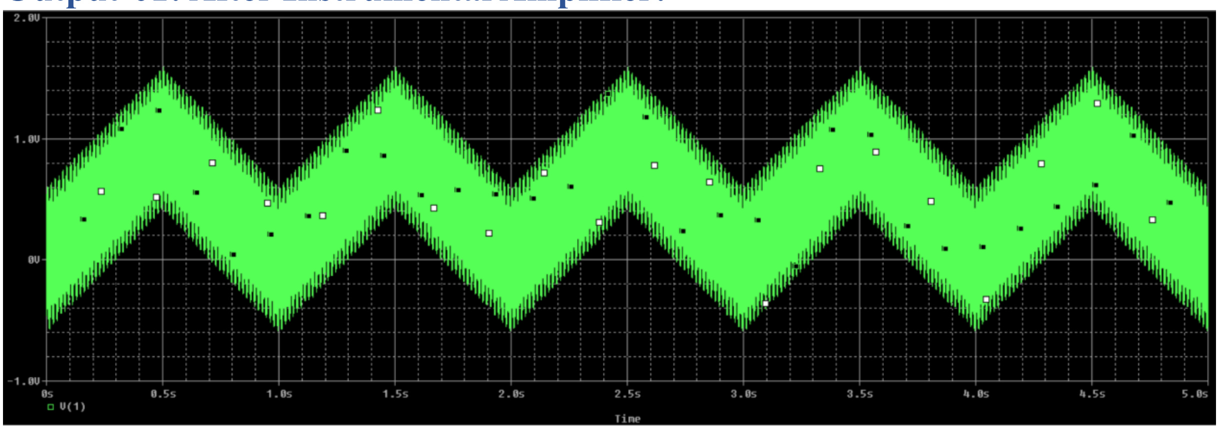


Simulation Results

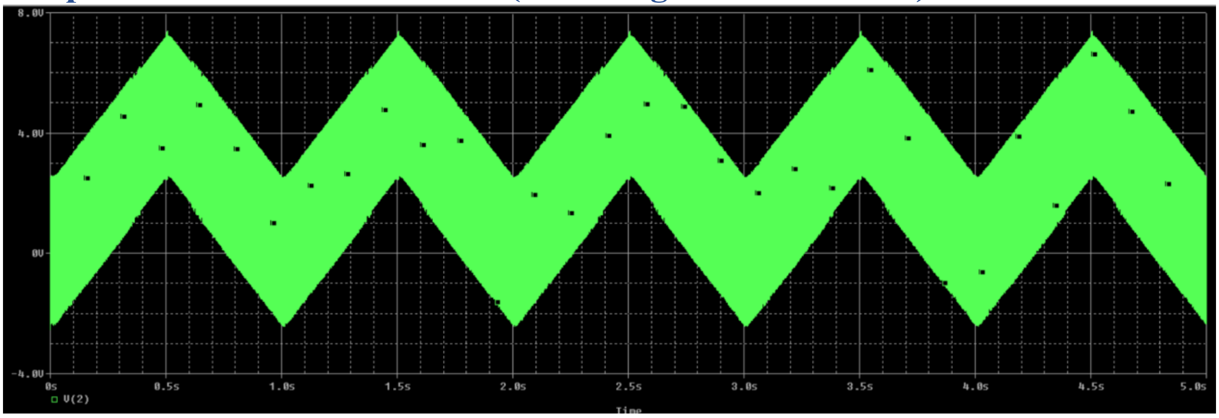
Amplification and noise cancellation:

We get an amplified and noise-free signal after passing the signal through the INSTRUMENTATION AMPLIFIER , A Notch Filter and A Passive low pass filter .

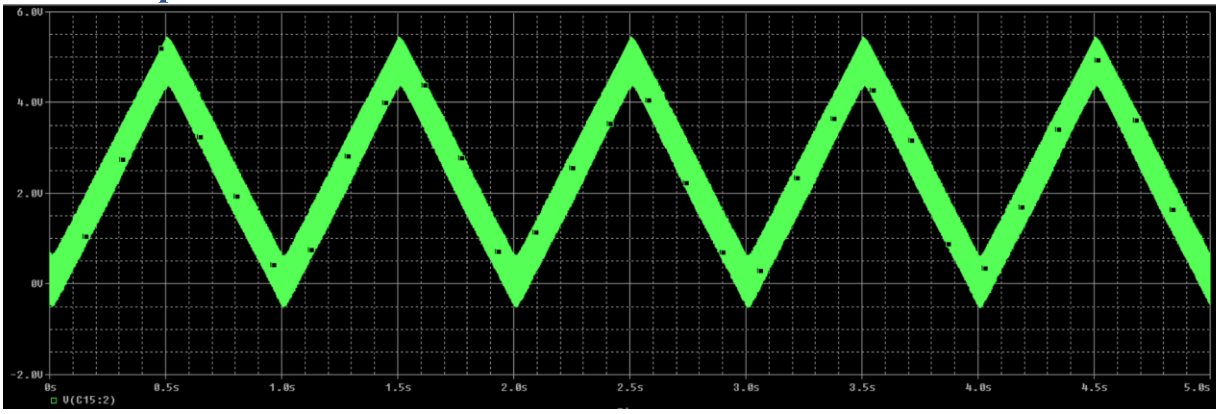
Output-01: After Instrumental Amplifier:



Output-02 : After Notch Filter: (Filtering the 60Hz Noise)



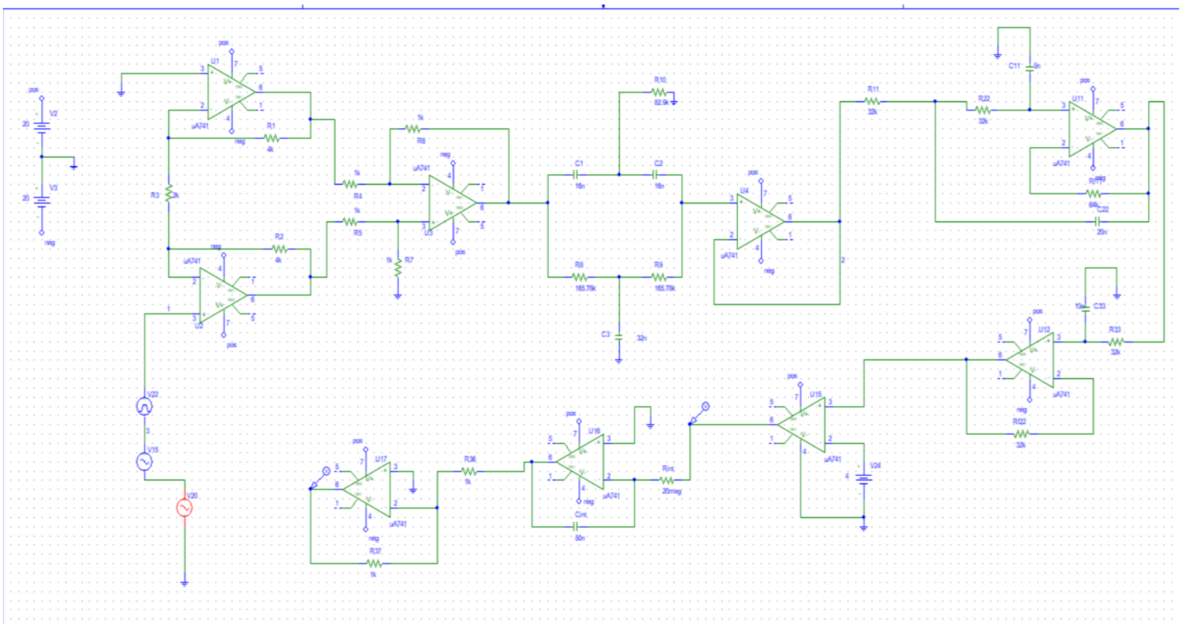
Final Output:



Output Analysis:

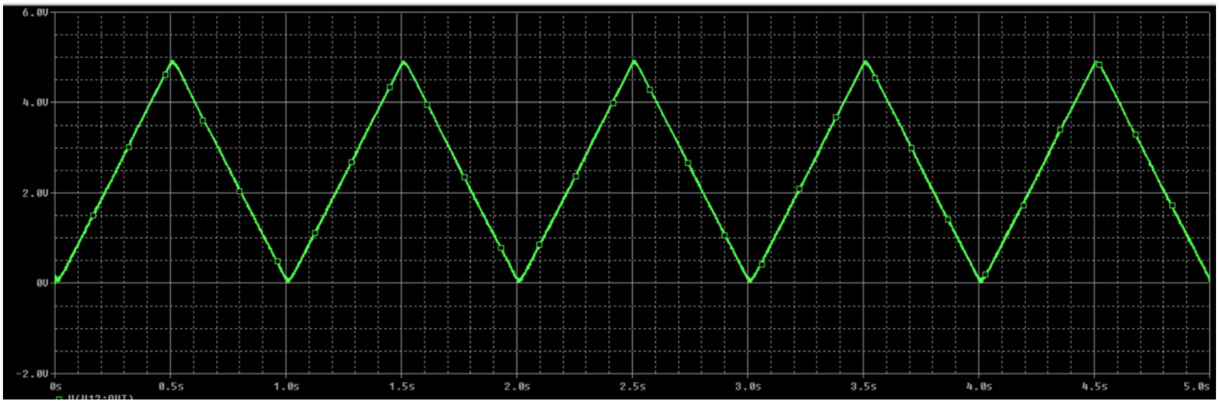
After filtering out the 60 Hz and 2 kHz noise from the triangular waveform, the resulting output waveform approximates the input signal. However, due to the use of passive filters, the output waveform does not fully replicate the expected shape, leading to some distortion. Additionally, the simulation encountered challenges related to the selection and tuning of capacitor values, which further contributed to deviations in the output waveform from the anticipated result. These limitations highlight the inherent trade-offs in using passive filter designs and underscore the need for careful parameter optimization in achieving desired performance.

Part-B : (With Active Filter) :



Simulation Results

Output :

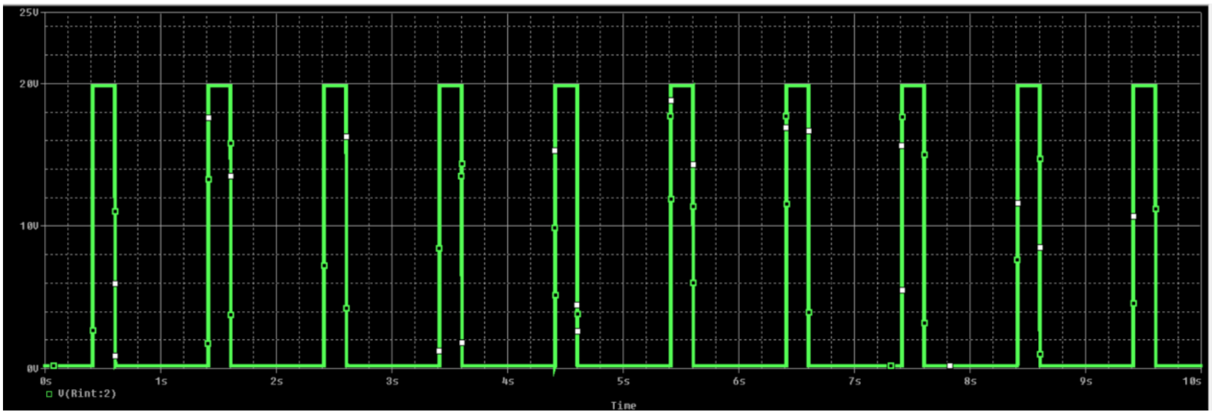


Output Analysis :

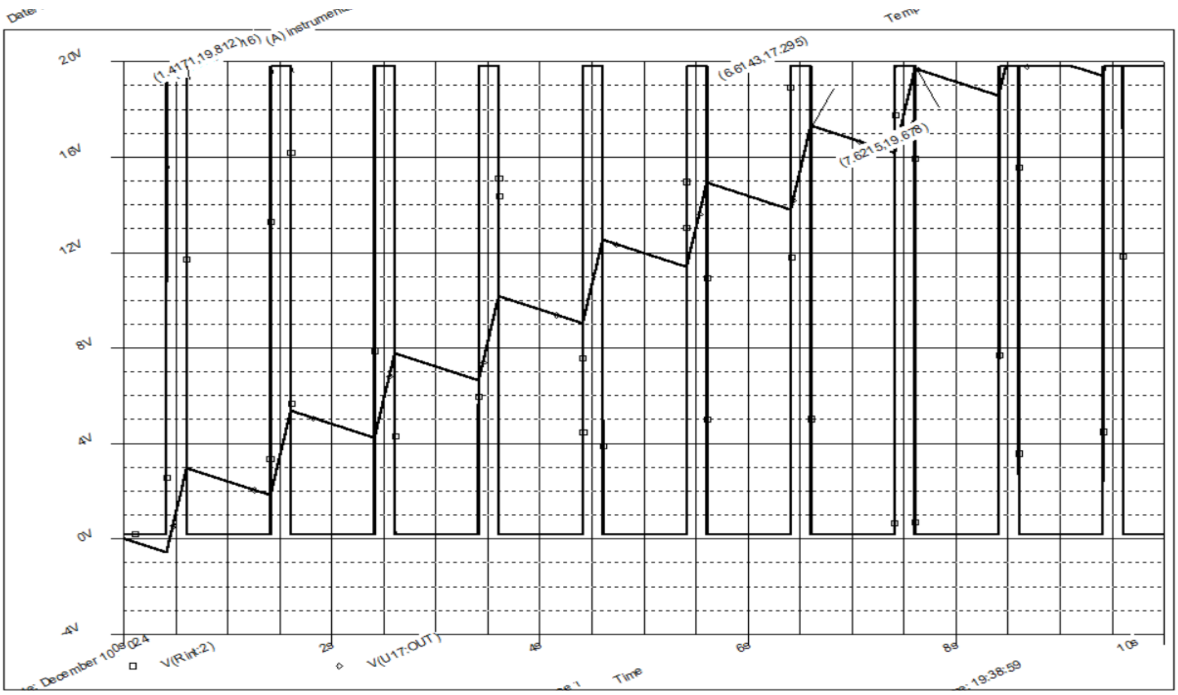
The graph demonstrates that the output waveform closely matches the expected waveshape without any noticeable deviations. This indicates that the noise originally mixed with the signal has been effectively eliminated. In this circuit, an active low-pass Butterworth filter with a roll-off rate of -60 dB per decade was utilized to remove high-frequency noise. The Butterworth filter's smooth frequency response and sharp cutoff characteristics contributed to achieving the desired noise suppression and restoring the integrity of the original signal.

Digital Signal:

When we pass the amplified and noise-free signal to the comparator, it outputs a high voltage level, creating a digital pulse.



Integrated Output: We integrate the area under the digital pulse and the area is 19.678 for 8 seconds. We calculated a single pulse area (19.678-17.295)= 2.4. We divided the total area by the single pulse area and then we calculated the total number of pulses for 60 seconds. To do this we used an inverting amplifier with a gain 1.



Total pulse in 8s is 19.678/2.4 = 8.1 ~ 8 .
So , Total pulse in 60s is (8/8)*60 = 60 BPM
Finally , the Heartrate = 60 BPM

Challenges and Solutions

1. Noise Filtration Accuracy

Challenge:
Effectively filtering out multiple noise components (60 Hz and 2 kHz) from the heart rate signal while preserving the integrity of the waveform was challenging. Passive filters, although simpler in design, were unable to maintain the waveform's fidelity, leading to distortion.
Solution:
To overcome this, we transitioned from passive filters to an active Butterworth low-pass filter. The Butterworth filter's -60 dB roll-off per decade and flat passband response ensured precise attenuation of high-frequency noise while maintaining the original waveform's shape.

2. Capacitor Value Optimization

Challenge:
During simulation, improper capacitor values in the filters caused deviations in the output waveform from the expected signal. These mismatched values led to unintended cutoff frequencies and reduced noise removal efficiency.
Due to Pspice technical limitations , it was unable to converge the voltage and current values for capacitors higher than nano farad order . For this reason, we were unable to choose the capacitor value in uF or mF range.

3. Peak Detection Consistency

Challenge:
Accurate detection of signal peaks was crucial for BPM calculation. However, the presence of residual noise after filtering occasionally caused false peak detections or missed actual peaks.
Solution:
A comparator circuit with carefully set thresholds was added to enhance peak detection reliability. Threshold values were calibrated to distinguish true peaks from noise artifacts, ensuring consistent and accurate BPM calculations.

Discussion and Limitations

Discussion

Accuracy: The project successfully demonstrated a reasonable level of accuracy in heart rate monitoring. As we use a pure triangular wave as input , we get 100% accuracy with the given circuit. Dealing with real data , the accuracy might deviate a little.

Performance: Our circuit performed quite well in a controlled, simulated environment. However, we recognize that the transition from a simulation to a real-world application presents additional challenges, including environmental factors and user variability.
Efficiency: While computational efficiency was fairly high, power efficiency remains an area to be investigated. This is particularly important for portable or long-term monitoring solutions.

Usability: The lack of a user interface makes it less accessible to non-technical users, suggesting the need for future work focused on usability and user experience.

Limitations

Despite the successful implementation and simulation of the heart monitoring system, the project has certain limitations that highlight areas for potential improvement:

1. **Use of Simulated Input Signal:**
    - Instead of using real-world heartbeat data, a triangular waveform was employed as the input signal. While this approach simplifies simulation, it does not fully represent the complexities of actual heartbeat signals, such as irregularities or varying amplitudes, which may affect the system's performance in real-world scenarios.
2. **Passive Filter Constraints:**
    - In initial designs, passive filters were used, which led to incomplete noise filtration and waveform distortion. Although replaced with active filters, this demonstrates the limitations of passive designs for such applications.
3. **Idealized Noise Models:**
    - The noise added to the input signal was modeled as specific frequencies (e.g., 60 Hz and 1.5 kHz). Real-world noise is often

more complex and may include unpredictable variations, which could pose additional challenges.

4. **Simulation-Specific Artifacts:**
   - Certain deviations in the output waveform were due to simulation-specific constraints, such as numerical precision and stability issues in PSpice. These artifacts might not directly translate to real-world hardware implementations but impact the simulation's accuracy.
5. **Simplified Peak Detection:**
   - The peak detection mechanism relies on a fixed threshold to identify beats. This method might not be robust enough to handle variations in amplitude or noise levels in real-world signals, potentially leading to inaccuracies in BPM calculation.
6. **Limited Validation of Filter Design:**
   - While the Butterworth filter provided satisfactory results in simulation, its performance under dynamic, real-world conditions (e.g., varying signal and noise characteristics) remains untested.
7. **Hardware Integration Not Addressed:**
   - The project focuses entirely on simulation, and no steps were taken to translate the design into a physical prototype. Hardware implementation could reveal additional challenges, such as component tolerances, power supply stability, and environmental factors.

Future Work

1. **Integration with IoT Devices:** A future extension could involve integrating the monitoring circuit with IoT-enabled devices for real-time data monitoring and alerts.

2. **Multi-Parameter Monitoring:** The circuit could be adapted to monitor other physiological parameters like blood oxygen(Pulse Oximeter) levels or body temperature.

3. **Advanced Modeling:** The next iterations could employ more complex models in Pspice to simulate body impedance, temperature changes, and other factors affecting the heart rate signal.

4) **Machine Learning for Anomaly Detection:** Advanced machine learning algorithms could be implemented in Python to identify abnormal
   a. patterns in heart rate data, providing more detailed insights and potentially lifesaving information.

5) Real-time implementation on hardware for validation.