

EEG Signal Filtering Method and Comparison Between Modern to Classical Filter

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Abstract. In neuroscience and therapeutic applications, electroencephalography (EEG) has become a crucial technique for gaining understanding of brain activity and cognitive processes. In order to improve signal quality, lower noise, and extract useful information from EEG data, preprocessing is essential. In the context of EEG signal processing, this study compares the effectiveness of three frequently used filtering methods: the median filter, average filter, and Gaussian filter. This study's main goal is to assess and compare how well these filters work to reduce the various forms of noise that may be found in EEG data, such as physiological artifacts, environmental interference, and electrode noise. The study makes use of a large dataset of EEG recordings that spans a range of experimental settings and mental states. The filtering methods are methodically applied to the unprocessed EEG data, and then the effects on signal fidelity and quality are thoroughly examined. The findings of this investigation shed important light on the advantages and disadvantages of each filtering strategy used in EEG data processing. In the end, the conclusions from this comparison study help offer criteria for choosing a suitable filtering approach based on the unique properties of EEG data and the research goals. The findings of this investigation offer important new understandings of the advantages and disadvantages of each filtering strategy used in EEG data processing. Finally, depending on the unique properties of the EEG data and the study goals, the findings from this comparison analysis help offer criteria for choosing an acceptable filtering approach.

Keywords: EEG signal filtering; modern and classical filter; filter design.

1. Introduction

An electronic device that measures the electrical impulses produced by the brain is known as an electroencephalography (EEG) sensor. EEG sensors generally record the fluctuating electrical signals produced over time by the activity of dense clusters of neurons close to the surface of the brain [1]. The development of electroencephalography (EEG) by the German psychiatrist Hans Berger in 1929 was a historical innovation that offered a new neurologic and psychiatric diagnostic tool at the time, especially in light of the absence of all those now commonly used in clinical settings (EP, CT, MRI, DSA, etc.), without which it would be impossible to make neurologic diagnoses and plan neurosurgical operations [2]. The EEG technology is widely used due to a few advantages such as non-invasiveness (This lessens ethical issues and enables wider use by making it safe and generally comfortable for subjects), real-time monitoring, and cost-effectiveness [3].

This paper will be mainly focus on the testing and comparing different filters we often used to pre-process the EEG data. Filter is a technique or electrical gadget used to increase acceptable signal components or eliminate undesirable ones. In general, the term "filter" can be used to denote a number of activities, including those that extract features, add or delete signal information, and interpret. Constructing three filter circuits (first-order high pass RC circuit, second-order butterworth filter and Twin-T notch filter) In order to remove the artifacts and interference in the signal, three filters which are average filter, median filter, and Savitzky-Golay(S-Golay) filter filter will be applied to see the efficiency in biomedical electrical signal. Also comparing the classical filter and modern filter's characteristics.

2. Methods

The brain signal EEG is complex also difficult to collect it, the EEG uses scalp electrodes to record voltage variations caused by the passage of electrical charge at each activation of the synapses in the brain's neurons [4]The EEG signal always divide into five bands which are Delta, Theta, Alpha, Beta and Gamma. These signal bands are key components of EEG signal analysis and gives important information about different states and functions.

Delta waves is within frequency range between 0.5 to 4Hz, they are the slowest and highest amplitude EEG waves, often detected with deep sleep stages. Theta waves is within frequency range between 4-8Hz, they are often seen during light sleep or deep relaxation. Alpha waves is between frequencies ranges 8-13Hz, detected when the person is awake during relax status. Often associated with calmness. Beta waves is between frequencies ranges 13-30Hz, it is appeared when active thinking and problem-solving. Gamma wave is between frequency range >30Hz, it is the fastest EEG signal, it is associated with cognitive [5].

After we have collected EEG signal, we can't immediately use in the real life. The EEG electrodes takes up a range of noise and artifacts throughout the EEG recording process rather than just the pure signal, the graph shown the BCI signal system acquisition, after passing those steps, the EEG signal can be accurately obtained. Figure 1 showed the EEG signal acquisition system.

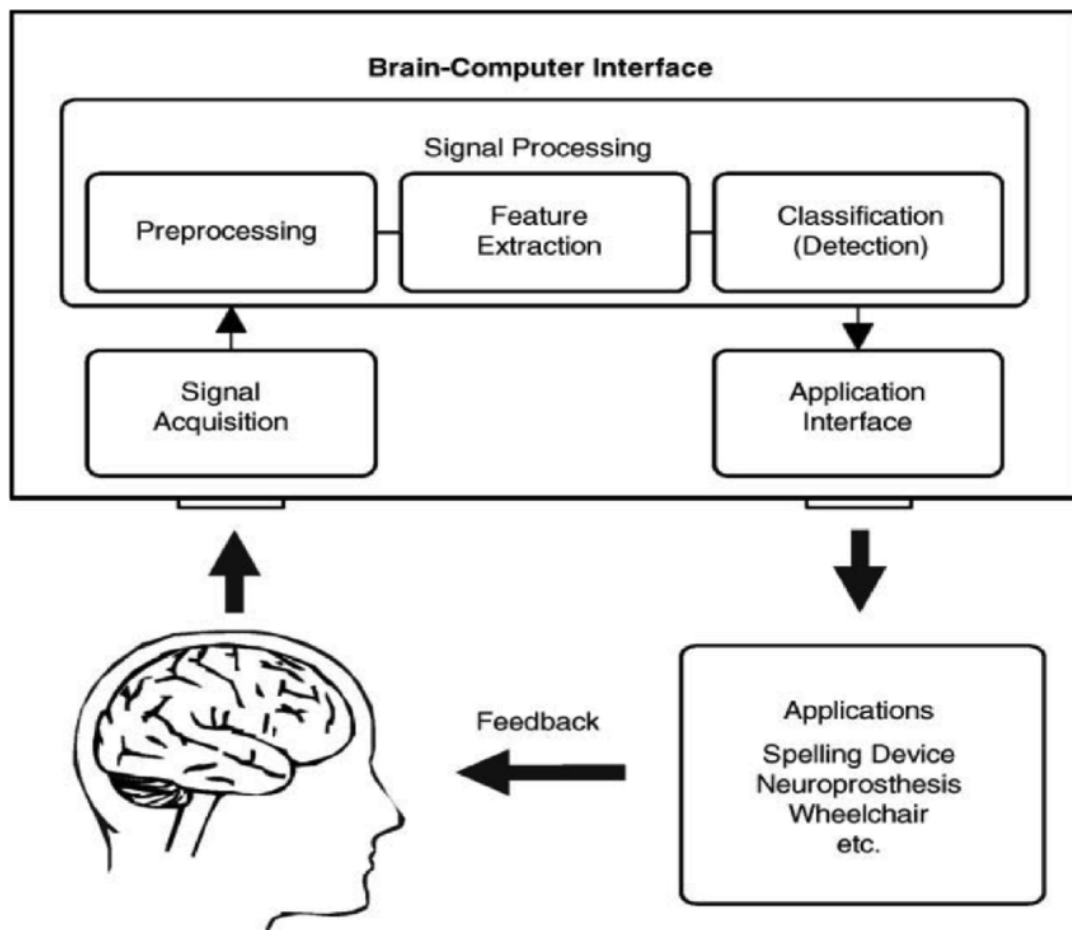


Fig 1. EEG signal acquisition system.

EEG signal artifacts are frequently irregular elements that can conceal or distort the real brainwave activity in an EEG recording. These artifacts can come from variety of physiological and non-physiological causes, and they present an important problem in the processing of EEG data.

This work will introduce the most important part which is signal preprocessing, mainly focus on the signal filtering stage. The function of the filter circuit is to reduce the AC component of the pulsating DC voltage as much as possible and retain its DC component, so that the output voltage ripple coefficient is reduced and the waveform becomes smoother. Filters can be divided into classic

filtering and modern filtering. A classic filter, also known as a filter circuit, is a device that only permits signal components falling within a specific frequency range to pass properly and forbids the passage of other frequency components. Modern filters, also known as modern signal processing, modern signal spectrum analysis, or statistical signal processing, are a collection of techniques for estimating or finding valuable signals from noisy data [6]. Figure 2 showed the preprocessing stages.

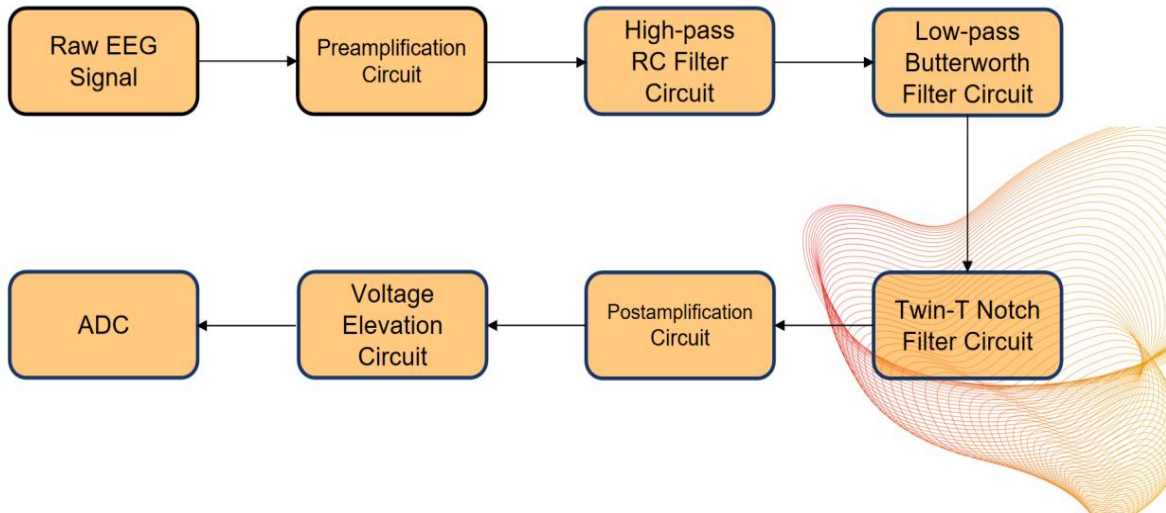


Fig 2. The preprocessing stages.

The signal filtering stage contains three parts which will pass through high-pass RC filter circuit, low-pass Butterworth filter circuit and Twin-T North filter circuit. High-pass RC filter is used to block the frequency under the frequency setting value, allow the high frequency to pass. Because of the range of EEG signal is mainly between 0.5 to 30Hz, so high pass filter can reduce the attenuating below the 0.5Hz frequency which is the minimum value within the Delta wave. Figure 3 showed first order high pass RC circuit.

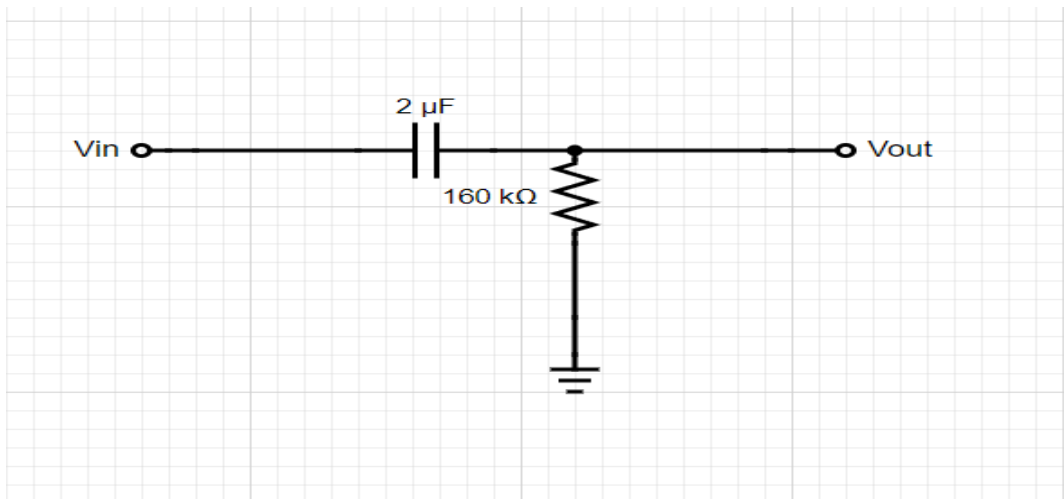


Fig 3. First order high pass RC circuit.

As the circuit diagram shown in Figure 3, this is just a simple first order high pass RC circuit with one resistor and one capacitor, this work will set the cut-off frequency to 0.5Hz, using the formula $f_c = \frac{1}{2\pi RC}$, choose capacitance to 2μF and resistance 160kΩ.

Next step is remove the frequency above 30Hz, this is the typical value for Beta wave which very often used in EEG signal. A second-order Butterworth filter will be used in this stage. This butterworth filter will provide a flat pass band and frequency response without ripple due to the Infinite Impulse Response filter. To design the second-order Butterworth filter, the Sallen-key filter circuit is the best during this situation. Figure 4 showed the generic Sallen-Key filter Topology.

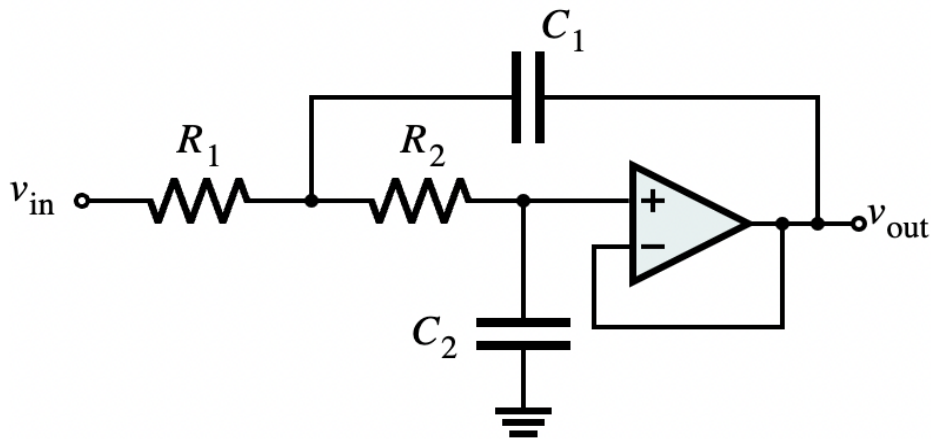


Fig 4. The generic Sallen-Key filter Topology [7].

During the circuit testing, I have realized that second-order filter can't fulfill my design goal, so this Sallen-Key filter circuit has cascaded with one RC circuit to achieve a third order Butterworth filter.

The butterworth filter is IIR filter (Infinite length unit impulse response filter), has feedback to the output. Comparing to FIR filter, IIR has infinite input response and historical output feedback, in the same order filter circuit will have better filter effect. IIR is more suitable to employ in circumstances when phase requirements are not important [8]. Figure 5 showed the factored butterworth polynomials.

Order	Factored Butterworth polynomials
1	$(s + 1)$
2	$(s^2 + 1.414s + 1)$
3	$(s + 1)(s^2 + s + 1)$
4	$(s^2 + 0.765s + 1)(s^2 + 1.848s + 1)$
5	$(s + 1)(s^2 + 0.618s + 1)(s^2 + 1.618s + 1)$
6	$(s^2 + 0.518s + 1)(s^2 + 1.414s + 1)(s^2 + 1.932s + 1)$
7	$(s + 1)(s^2 + 0.445s + 1)(s^2 + 1.247s + 1)(s^2 + 1.802s + 1)$
8	$(s^2 + 0.390s + 1)(s^2 + 1.111s + 1)(s^2 + 1.663s + 1)(s^2 + 1.962s + 1)$

Fig 5. The factored butterworth polynomials [9].

When first-order RC circuit cascaded with second-order Sallen-Key circuit, using the factored butterworth polynomials graph to get the circuit flow diagram. It will help me to construct the circuit more easily. Each order corresponding to one polynomial, to realize the higher order filter, just cascading more RC circuit or second-order circuit. The q-factor can be found using this polynomial (only in second-order part). Figure 6 showed the 3rd order polynomial.

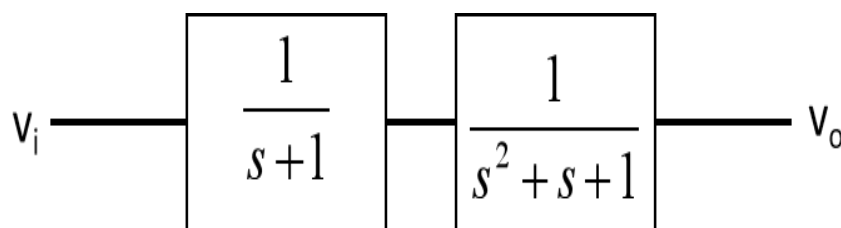


Fig 6. 3rd order polynomial [9].

Setting cut-off frequency equals to 30Hz, after that the circuit diagram is shown below. Figure 7 showed the 3rd order butterworth filter.

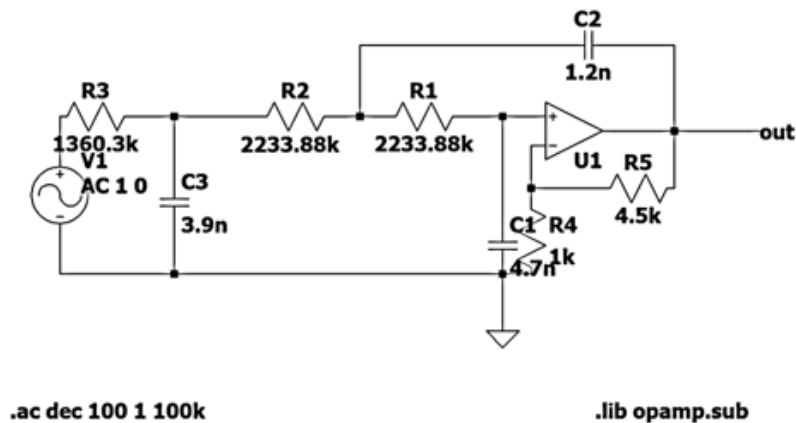


Fig 7. 3rd order butterworth filter.

This circuit was created using LTspice software, the left part is the RC circuit and AC voltage source, cascading with second-order Sallen-Key circuit. The resistor R4 and R5 are used for negative feedback.

$$q = \frac{1}{2} * \sqrt{\frac{C1}{C2}} \quad (1)$$

$$f0 = \frac{1}{2\pi R * \sqrt{C1 * C2}} \quad (2)$$

These two equation above can calculate the value for component value, the q which is q factor, it is the dimensionless parameter that quantifies how sharply the system resonates in response to an external force or disturbance [10]. A high Q factor means that the system can store a lot more energy than it expels through each cycle. To put it another way, it has a small bandwidth and a strong resonance. The Q factor is used in electrical circuits to describe the performance and selectivity of resonant circuits, such as inductors and capacitors in frequency filters.

In order to choose the suitable value of C1, this work would like to use the E series E12 and E24, these criteria are the standard sets of preferred values for electronic component, especially capacitors, resistors and inductors. By using these series, it is possible to guarantee that electrical components are produced in readily accessible quantities that are spaced to make it easier to design and manufacture circuits [11]. Finally, this work have chosen the value of C1=4.7nF, use formula one can get C2=1.2nF.

F0 is the cut-off frequency in the designed filter, to explain the formula, the transfer function needs to be explained. For the second order circuit we can see:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + \frac{s}{(\frac{\omega 0}{\omega c})q} + \frac{s^2}{(\frac{\omega 0}{\omega c})^2}} \quad (3)$$

$$\left(\frac{\omega 0}{\omega c}\right) = 1 \quad (4)$$

Comparing to the factored butterworth polynomial with third order filter. So the 1/q factor equals to 1. The

$$\omega 0 = \frac{1}{R\sqrt{C1C2}} \quad (5)$$

Can be derived. Using f0=30Hz, get R1=R2=2233.88kohm. The first order RC circuit should calculate separately,

$$f O = \frac{1}{2\pi RC} \quad (6)$$

Same as the second order circuit, choose the value of capacitor first, $C_3=3.9\text{nF}$. The value of $R_3=1360.3\text{kohm}$.

After constructing circuit, the next step is running the simulation in the software. This graph contains two important information, magnitude response and frequency response, which corresponding to two curves shown in the graph. The y-axis in the left represents voltage gain in db and x-axis is the frequency range in the scale of logarithm. Before the curve starting bending, this part is the pass band frequency and the curve part is the stop band. The value of cut-off frequency is located in the (maximum gain-3) in y-axis corresponding to x-axis point. In the graph we can see the cut-off frequency is approximately equal to 30Hz. The stop band will produce roll off=-40db/decade because of second-order filter, each order will provide -20db/decade. By calculating the slope of the curve. The roll off of a filter is the rate at which the response of the filter attenuates as the cut-off frequency move away. The dot curve shows the frequency response in degree. Each order of filter will provide -90 degree, so total -270degree. Through the data received in the graph, the construction of circuit has meet my specification, it block the frequency above the 30Hz. Figure 8 showed the magnitude/frequency response graph.

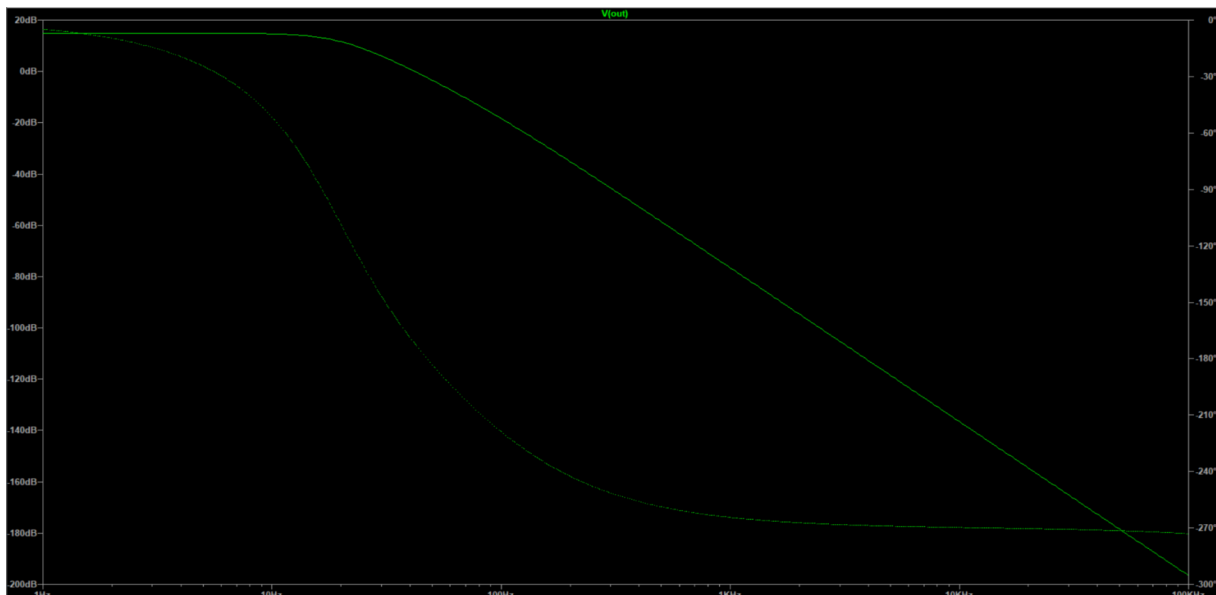


Fig 8. Magnitude/Frequency response graph.

Also, increasing the number of order with filter can provide more smooth stop band, which will provide sharper roll-off, the rate of filter attenuates frequencies outside the passband become steeper, provide more efficiently filtering rate. In the other hand, higher order filter will have flat frequency response, there is less ripple within the amplitude. This advantage can reduce the distortion effectively [11]. But increase also increase the cost and complexity of the filter circuit. The group delay during the signal transmission would increase because more time needed to receive the information. The choice of number of orders is mainly connected to the real demand situation. Because of the range of EEG signal is between 0.5-100Hz, there is another interference point need to remove that is the 50Hz signal. This kind of artifact is typically attribute by electrical interference in power line signal may be contaminated by this noise, make it difficult to isolate significant brain activity.

To eliminate the 50Hz noise, the twin-T notch filter should be used. This filter could be used in a variety of applications, such as audio signal processing and electronic circuit design, since it is particularly good at removing the unwanted noise or interference at particular frequency. According to the values of capacitors and resistors, the cut-off frequency can be compute. The notch filter mainly designed with low pass filter with cut-off frequency f_1 and high pass frequency with cut-off frequency f_2 parallel to each other, and the frequency $f_1 < f_2$, when the signal pass through the circuit, the frequency range larger than f_2 and smaller than f_1 will pass, only cut the frequency between them. But this cause another problem appear, the passive twin-T notch filter has low input impedance and

high output impedance, it is susceptible to the influence of the front and rear stages of the circuit. To solve this problem, add opamp system is a good choice.

This work have chosen the opa1656 as the opamp system, this opamp can provide excellent audio performance. It features a low degree of harmonic distortion and very strong dynamic range. It may replace several other versions since it can take use of a board power supply range and is installed on a DIP8 bracket [12].

As shown in Figure 9, this circuit is active Twin-T notch filter, combined two opamp with Twin-T filter, also included negative feedback in the circuit, opamp U1 provide the feedback's gain, isolation the twin-t network.

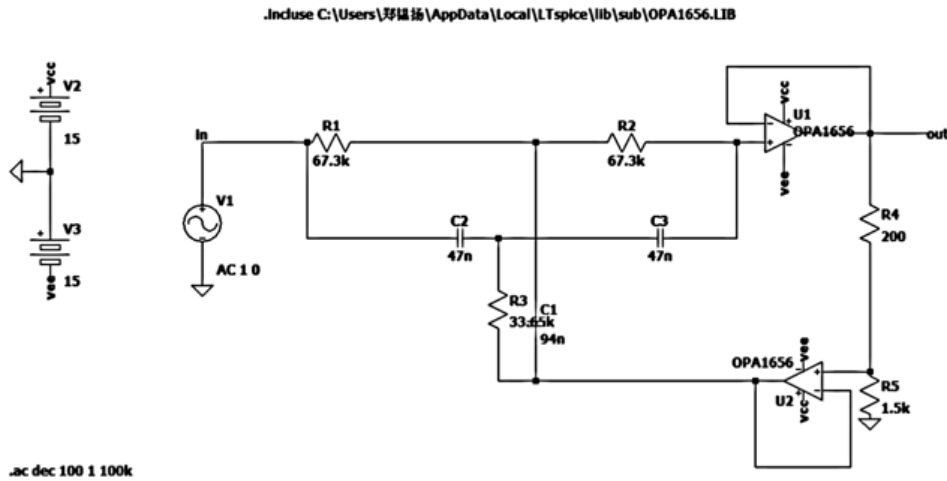


Fig. 9. Twin-T notch filter circuit diagram

Two equations needed to calculate the component value, $f_0 = \frac{1}{2\pi RC}$ is the cut-off frequency, and $Q = \frac{1}{4(1-k)}$, $R4 = (1-k)RF$ is feedback resistor. Coefficient k decide the width of stop band, increase the k will decrease the width, the quality factor increase and improve the efficiency of notch filter. Decrease the k, the efficiency will decrease but improve the stability [13].

For 50Hz notch filter, quality factor can equal to 2.5, capacitance equals to 47nF, from the formula can get R=67.3kohm, Rf= 2kohm (R4=200ohm andR5=1.8kohm from coefficient).The graph shows the 50Hz frequency has been removed. Figure 10 showed the simulation graph of notch filter.

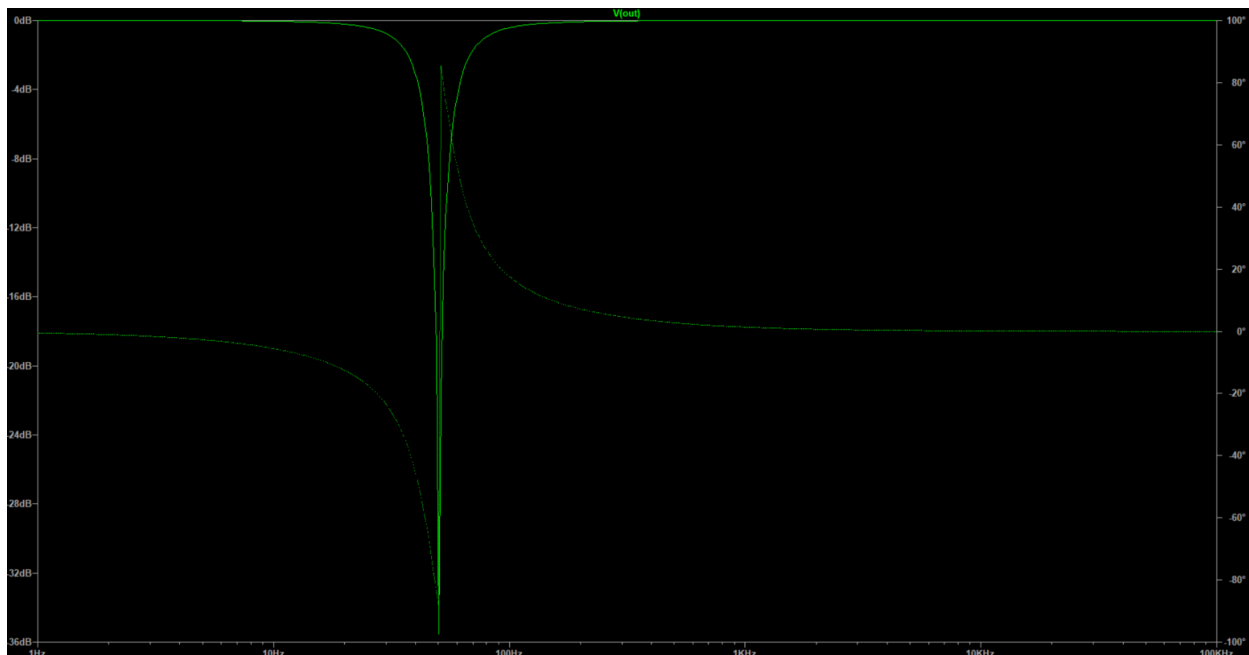


Fig 10. Simulation graph of notch filter.

When the filter settings are fixed independent of the input signal once the design has been chosen. The usefulness of the classic filter may be significantly diminished in some engineering practice scenarios where the filter's parameters must vary even while the signal does not, or where the signal parameters are random numbers, etc. We must make advantage of contemporary filtration technology in these circumstances. This work would like to introduce three others modern filter, Savitzky-Golay(S-Golay) filter, median filter and moving average filter [14].

Savitzky-Golay filter is a popular method for smoothing or reducing noise in digital signal processing, this filter, which bears the names of its creators Abraham Savitzky and Marcel J.E Goalties renowned for its capacity to filter out noise from data while retaining significant characteristics and patterns in the signal. The property of S-G filter is applied EEG signal processing. According to its working principle, each value is replaced with a new value. The selected data points N will have the polynomial fitting of data, the choice of polynomial order depends on the type of data. Higher order polynomials may introduce more smoothing but can also capture more complicated patterns [14]. Uses can customize the filter's settings, such as the window size and polynomial order, to meet their own demands for smoothing. The trade-off between feature retention and noise reduction may be adjusted because to this flexibility. Figure 11 showed the S-G filtering output with white noise.

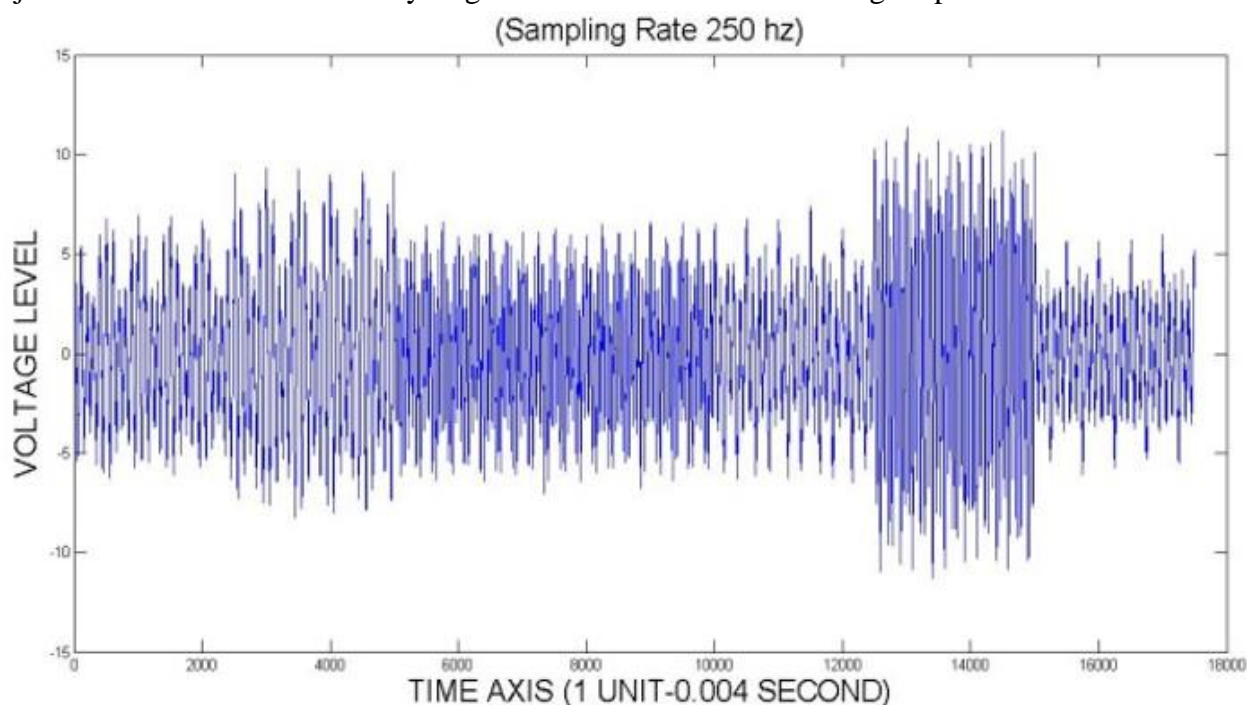


Fig 11. S-G filtering output with white noise [14].

There are some disadvantages like in large window size and higher order S-G filter, the filter will be expensive. Also, the S-G filter cannot be suitable for signal for non-polynomial characteristics.

A median filter is a non-linear filter commonly used in image processing and noise reduction, it is effectively at reducing the impact of salt-and pepper noise(impulse noise).Median filters are appropriate for situations where maintaining crisp transition is important because they do not blur edges or small details in pictures or signals [15]. The median values of each window individually make up the output signal. The moving median procedure, which is similar to the moving average but is thought to be preferable for some applications, may be used to apply the filter to offline data. However, in the real time application, median filter can be computationally demanding for large neighborhoods and choosing an appropriate neighborhood size can be very challenging.

The third filter widely employed to time-series data is moving average filter, it is commonly used applications where the focus on the extracting long-term trends from noisy data, rather than rapid fluctuations. The data points are averaged inside the chosen window to get a signal value. The center data point inside the frame is then given the estimated average value. This filter method has higher efficiency and simplicity, effectively removing the high-frequency noise and fluctuations in data,

making them smoothing application. Finally, the data's unique properties and the intended trade-off between noise reduction and feature retention determine the filter to use [15]. Moving average filters offer straightforward and effective smoothing, while median filters are excellent at eliminating impulsive noise, S-Golay filters strike a compromise between noise reduction and feature retention.

3. Discussion

Overall, EEG signal processing is a large topic for me to discuss. Expecting from the high/low pass filtering like butterworth filter and time-domain filtering like moving average, there are other filtering method such as adaptive filtering and wavelet transform filtering. The goal for these methods are almost the same but the results are different in some perspective. The EEG data has unique properties, the kind of noise and artifacts present, and the analysis's objectives all influence the filtering method(s) that are used. To improve the preparation of EEG data, several filtering procedures may often be used. In order to prevent accidentally changing the desired EEG signal, it is also crucial to carefully evaluate filter parameters (such as filter order and cutoff frequencies). It is difficult to choose the suitable filter circuit design, to meet the specification in Twin-T notch filter, the choice of opamp may have better option.

4. Conclusion

Comparing the classical filter and modern filter, the main distinction between classic filters and modern filters is that, in order to achieve signal purification, target feature extraction, and other objectives, traditional filters often leave certain components and weaken others from a frequency viewpoint. Modern filtering performs extensive study and debate with the goal of distinguishing noise from important target signals and reducing noise, but does not work on particular frequency ranges. Modern filtering techniques are frequently more adaptable and versatile. They are able to adjust to the unique EEG data properties, which might change from person to person or even within a single recording session. Traditional filters are a preferred option for many applications because they are well-known and computationally effective. The computing requirements of modern techniques might be higher. In conclusion, while adaptive filtering and wavelet transform are more flexible and may be more appropriate for some EEG analysis tasks, classical EEG signal filtering techniques like Butterworth filters are still widely used and effective. This is especially true when dealing with non-stationary signals or when maintaining both time and frequency information is important. Based on the particular needs of the EEG investigation, the filtering strategy should be chosen.

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