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Design and Analysis of an Operational-Amplifier-Based 50 Hz Notch Filter for Biomedical Signal Processing

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ABSTRACT

Biomedical signals such as electrocardiograms (ECG), electroencephalograms (EEG), and electromyograms (EMG) are typically low-amplitude signals that are susceptible to power-line interference, electrode noise, and environmental electromagnetic disturbances. In India and many other countries, electrical mains interference occurs at 50 Hz and can obscure important signal characteristics. This paper presents the theoretical design of an active 50 Hz notch filter using an operational amplifier (op-amp) and a twin-T resistor–capacitor network. The proposed circuit is intended to attenuate the unwanted 50 Hz component while allowing frequencies outside the notch region to pass. The notch frequency is determined by the resistor and capacitor values, and the filter response depends on component tolerances, operational-amplifier characteristics, and network loading. A nominal design using 10 kΩ resistors and 320 nF capacitors gives a theoretical notch frequency of approximately 49.7 Hz. The paper discusses circuit implementation, mathematical modelling, component selection, expected performance, and biomedical applications. Simulation and experimental verification are proposed as the next stages of development; no measured performance is claimed in this manuscript. Particular attention is given to preserving diagnostically relevant ECG morphology and ensuring electrical safety in biomedical instrumentation.

Keywords: Active notch filter; operational amplifier; twin-T network; 50 Hz interference; ECG; EEG; EMG; biomedical instrumentation; signal conditioning; power-line noise.

1. INTRODUCTION

Biomedical instrumentation requires accurate acquisition and processing of physiological signals. ECG records the electrical activity of the heart, EEG measures electrical activity of the brain, and EMG records the electrical activity associated with skeletal muscles. These signals may have amplitudes ranging from microvolts to millivolts, making them particularly sensitive to external interference.

Power-line interference at 50 Hz can enter a biomedical acquisition system through capacitive coupling, inductive coupling, grounding problems, electrode impedance imbalance, and other electromagnetic effects. This interference may introduce periodic oscillations into the recorded waveform, affecting subsequent analysis and feature extraction.

A notch filter is a band-stop filter designed to attenuate a narrow range of frequencies around a selected centre frequency while preserving frequencies outside that range. An active notch filter combines resistors and capacitors with an operational amplifier to provide buffering, improved network isolation, and, in suitable configurations, enhanced selectivity.

1.1 Problem Statement

The main problem addressed in this work is the suppression of 50 Hz mains interference without unnecessarily attenuating useful biomedical signal components. A practical filter must attenuate interference close to 50 Hz, maintain acceptable signal amplitude and waveform fidelity outside the rejection band, and

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operate reliably despite component tolerances, amplifier limitations, and variations in the interference frequency.

1.2 Objectives

1. To develop a theoretical design for an op-amp-based 50 Hz notch filter.
2. To calculate suitable resistor and capacitor values.
3. To explain the filter's transfer function and operating principle.
4. To propose simulation and experimental methods for evaluating attenuation, bandwidth, and signal preservation.
5. To discuss its suitability and limitations for ECG, EEG, and EMG applications.

2. LITERATURE REVIEW

Notch filtering is a widely used approach for reducing power-line interference in biomedical signal acquisition. Published work has investigated 50 Hz active analogue notch-filter topologies for online ECG systems, low-power notch filters for biomedical applications, and digital notch-filter implementations. Research on portable ECG systems has also described the use of twin-T networks with operational amplifiers to reduce mains interference.

Prior studies also indicate that removing power-line interference does not automatically guarantee an undistorted biomedical signal. The attenuation band can overlap useful signal components, and notch-filter application can affect waveform morphology under certain recording conditions. Therefore, filter evaluation should consider both frequency-domain rejection and time-domain signal fidelity.

The present paper focuses on an accessible component-level analogue design that can be developed for laboratory demonstration and subsequently evaluated through circuit simulation and measured signals.

3. THEORETICAL BACKGROUND

3.1 Principle of a Notch Filter

A notch filter rejects signals within a narrow frequency band centred on the notch frequency f_0. For biomedical applications, the target frequency is commonly selected as 50 Hz in regions using 50 Hz electrical mains.

The quality factor Q is defined as:

$$\mathbf{Q = f_0 / BW}$$

where BW is the bandwidth between the lower and upper cutoff frequencies associated with the notch response. A high-Q filter has a narrower rejection band, while a lower-Q filter rejects a broader range of frequencies. The optimum value depends on the stability of the interference frequency and the need to preserve nearby signal components.

3.2 Twin-T RC Network

The twin-T network comprises two T-shaped networks connected in parallel: a resistive T-network consisting of two equal series resistors and a shunt capacitor, and a capacitive T-network consisting of two equal series capacitors and a shunt resistor.

$$\mathbf{R_1 = R_2 = R, \quad R_3 = R/2}$$

$$\mathbf{C_1 = C_2 = C, \quad C_3 = 2C}$$

$$\mathbf{f_0 = 1 / (2\pi RC)}$$

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At the notch frequency, the signals through the two network paths cancel under ideal balanced conditions,

producing an attenuation minimum. Component mismatch and loading reduce the practical notch depth.

3.3 Operational Amplifier Function

The operational amplifier can be configured as a voltage follower or incorporated into a feedback arrangement. A voltage follower provides high input impedance, low output impedance, and reduced loading between circuit stages. However, a simple voltage follower does not by itself guarantee a high-Q notch. An active twin-T feedback configuration can improve selectivity, but its performance depends on the chosen topology and component ratios.

4. PROPOSED CIRCUIT DESIGN

The proposed circuit uses a balanced twin-T RC network and an operational amplifier for buffering or active feedback. The complete schematic must specify the exact op-amp connections, network input/output nodes, and feedback path before its detailed frequency response can be predicted accurately.

4.1 Design Specifications

Parameter	**Proposed value**
Application	Biomedical signal conditioning
Target notch frequency	50 Hz
Filter topology	Twin-T RC network with op-amp buffering
Nominal resistor R	10 kΩ
Nominal capacitor C	320 nF
Calculated notch frequency	49.74 Hz
Op-amp configuration	Voltage follower or suitable active-feedback topology
Signal types	ECG, EEG, EMG
Verification method	SPICE simulation and laboratory testing

4.2 Component Selection

Component	**Value**	**Function**
R_1	10 kΩ	First series resistor
R_2	10 kΩ	Second series resistor
R_3	5 kΩ	Shunt resistor (R/2)
C_1	320 nF	First series capacitor

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C_2	320 nF	Second series capacitor
C_3	640 nF	Shunt capacitor (2C)
U1	Suitable low-noise op-amp	Buffer or active stage

Practical component selection may use parallel resistor or capacitor combinations to obtain the required values. Matched resistors and capacitors are recommended because component mismatch can reduce notch depth. The amplifier should be selected according to supply voltage, signal range, input common-mode range, input noise, offset voltage, and output swing. A TL072 may be suitable for a laboratory prototype with an appropriate dual supply; a low-noise, low-power rail-to-rail amplifier may be preferable for a battery-operated design.

4.3 Notch-Frequency Calculation

Given:

$R = 10{,}000\ \Omega$

$C = 320 \times 10^{-9}\ F$

$$\mathbf{f_0 = 1 / (2\pi RC)}$$

$$\mathbf{f_0 = 1 / [2\pi \times 10{,}000 \times (320 \times 10^{-9})]}$$

$$\mathbf{f_0 \approx 49.74\ Hz}$$

For an exact nominal 50 Hz design using R = 10 kΩ, the required capacitance is:

$$\mathbf{C = 1 / (2\pi f_0 R) = 1 / [2\pi \times 50 \times 10{,}000] \approx 318.3\ nF}$$

Thus, a nominal capacitance of approximately 318 nF with 10 kΩ resistors gives a theoretical 50 Hz notch. Actual performance depends on component tolerances and circuit loading.

4.4 Operational Amplifier Configuration

For a voltage follower, the output is connected directly to the inverting input, and the signal is applied to the non-inverting input. Ideally, Vout ≈ Vin. This configuration provides buffering rather than additional voltage gain.

For a more selective active notch filter, the twin-T network can be incorporated into an op-amp feedback circuit. The feedback factor and component ratios must be derived for the selected topology; the circuit should not be assumed to achieve a particular Q or attenuation without analysis or simulation.

5. MATHEMATICAL ANALYSIS

5.1 Ideal Transfer Function

A standard second-order notch response can be represented by:

$$\mathbf{H(s) = K(s^2 + \omega_0^2) / [s^2 + (\omega_0/Q)s + \omega_0^2]}$$

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where H(s) is the transfer function, K is the passband gain, $\omega_0 = 2\pi f_0$ is the angular notch frequency, Q is the quality factor, and s is the Laplace variable.

For a 50 Hz target, $\omega_0 = 2\pi(50) \approx 314.16$ rad/s. For an illustrative ideal design with Q = 10 and unity passband gain:

$$\mathbf{H(s) = (s^2 + 98{,}696) / (s^2 + 31.416s + 98{,}696)}$$

This equation represents an ideal second-order notch response. It does not establish that the specified buffered twin-T circuit will achieve Q = 10; that requires a corresponding active-feedback design.

5.2 Frequency Response

The magnitude response of the ideal transfer function is:

$$\mathbf{|H(j\omega)| = |K|\ |\omega_0^2 - \omega^2| / \sqrt{[(\omega_0^2 - \omega^2)^2 + (\omega\omega_0/Q)^2]}}$$

At the ideal notch frequency, the numerator becomes zero, yielding idealized zero transmission. A physical circuit generally has finite attenuation because of component mismatch, parasitic effects, amplifier limitations, and noise.

5.3 Expected Response Characteristics

Frequency region	Expected behaviour
Well below 50 Hz	Signal passes with approximately the designed passband gain
Near 50 Hz	Strong attenuation of the targeted interference
Well above 50 Hz	Signal passes according to the designed frequency response
Near the notch edges	Response depends on notch bandwidth and Q

The actual response must be measured or simulated. A notch filter alone does not eliminate baseline wander, broadband noise, motion artefacts, or interference at other frequencies.

6. SIMULATION METHODOLOGY

The proposed circuit can be evaluated using LTspice, NI Multisim, Proteus, or another SPICE-compatible circuit simulator.

1. Construct the balanced twin-T network using the specified resistor and capacitor values.
2. Connect the operational amplifier in the selected buffer or active-feedback configuration.
3. Select an appropriate power supply and verify the amplifier's operating limits.
4. Perform AC analysis over a frequency range of approximately 1 Hz to 1 kHz.
5. Plot the output-to-input voltage ratio in decibels.
6. Record the frequency of minimum gain, notch depth, bandwidth, and passband gain.
7. Repeat the analysis with realistic component tolerances.
8. Apply a synthetic ECG waveform with an added 50 Hz sinusoidal disturbance and compare the input and output waveforms.

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6.1 Proposed Simulation Test Conditions

Test	Input	Measurement
1	AC sweep	Notch frequency and magnitude response
2	50 Hz sine wave	Attenuation at the target frequency
3	10 Hz sine wave	Passband amplitude preservation
4	Synthetic ECG plus 50 Hz interference	Waveform fidelity and residual interference
5	Component tolerance variation	Notch-frequency shift and notch-depth variation

Performance should be evaluated using both frequency response and time-domain waveforms. A visually smoother ECG signal alone is not sufficient evidence of improved diagnostic accuracy.

7. RESULTS AND DISCUSSION

7.1 Theoretical Results

The component calculations yield a notch frequency of approximately 49.74 Hz for R = 10 kΩ and C = 320 nF. This result is derived from the ideal balanced twin-T relationship. No circuit simulation or physical experiment has been performed for this manuscript. Consequently, notch depth, measured bandwidth, output noise, and improvement in signal-to-noise ratio remain to be established.

Performance parameter	Result to obtain
Notch frequency	Measured centre frequency in Hz
Notch depth	Measured attenuation in dB
Quality factor	Calculated from measured bandwidth
Passband gain	Measured gain outside rejection band
Signal-to-noise ratio	Before and after filtering
ECG waveform fidelity	Quantitative comparison of waveform morphology
Component sensitivity	Response under tolerance variation

7.2 Notch Depth

Notch depth is defined as the difference between passband magnitude and minimum magnitude at the notch frequency:

$$A_{notch} = 20 \log_{10}(V_{passband} / V_{notch})$$

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For example, if the measured passband amplitude is 1 V and the output amplitude at 50 Hz is 10 mV, the attenuation is $20 \log_{10}(100) = 40$ dB. This is an illustrative calculation, not a measured result of the proposed circuit.

7.3 Biomedical Signal Preservation

The principal design challenge is balancing power-line suppression against preservation of useful signal information. ECG waveform features, including the P wave, QRS complex, and T wave, must remain sufficiently undistorted. For EEG and EMG, the effect of removing the 50 Hz component must also be assessed against the useful signal spectrum. Where feasible, interference prevention at the electrode, cable, grounding, and acquisition stages should be used alongside filtering.

8. BIOMEDICAL APPLICATIONS

8.1 Electrocardiography (ECG)

The filter can reduce mains-frequency interference in ECG acquisition systems, potentially improving waveform readability. Diagnostic use requires verification that the ST segment, QRS complex, and other relevant features are preserved.

8.2 Electroencephalography (EEG)

The filter can suppress electrical mains contamination in EEG recordings. Care is required because useful spectral information may occur near the rejection frequency.

8.3 Electromyography (EMG)

The filter can reduce narrowband interference in muscle-activity measurements. Its suitability depends on the EMG bandwidth and the intended physiological analysis.

9. LIMITATIONS AND FUTURE SCOPE

- Twin-T balance depends on accurate resistor and capacitor ratios. Precision components or trimming may be necessary.
- The actual interference frequency may vary; a fixed-frequency filter may become less effective if the interference moves away from its designed notch.
- Input noise, offset voltage, bandwidth, slew rate, output swing, and supply voltage can influence op-amp performance.
- A notch filter may attenuate useful components near 50 Hz and change the time-domain waveform.
- Harmonics at 100 Hz, 150 Hz, and other frequencies may remain after 50 Hz filtering.
- A prototype must not be connected directly to a person without an appropriately designed, isolated, and safety-verified biomedical front end.

Future work should include SPICE simulations, hardware measurements, tolerance analysis, and testing with appropriately sourced ECG, EEG, or EMG datasets. Performance should be compared with alternative analogue and digital filtering techniques.

10. CONCLUSION

This paper presents the theoretical design of an operational-amplifier-based twin-T notch filter intended for 50 Hz interference suppression in biomedical instrumentation. Using 10 kΩ resistors and 320 nF capacitors, the calculated notch frequency is approximately 49.74 Hz. A nominal 50 Hz design can be obtained using a capacitance of approximately 318.3 nF with 10 kΩ resistors.

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The operational amplifier provides buffering or, in an appropriately designed feedback topology, can improve the selectivity of the active filter. The final performance depends on the complete circuit configuration, component matching, and amplifier characteristics. Although theoretical calculations establish the design frequency, experimental verification is required to establish actual notch depth, bandwidth, signal-to-noise improvement, and biomedical waveform fidelity.

The proposed design provides a foundation for further development of low-cost analogue signal-conditioning systems for ECG, EEG, and EMG applications. It should be regarded as a research prototype concept rather than a clinically validated medical device.

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