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A MAJOR PROJECT REPORT
ON

CFOA BASED FILTER REALIZATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF
MASTERS OF TECHNOLOGY
IN
CONTROL & INSTRUMENTATION

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CANDIDATE'S DECLARATION

I Pragati Sattavan, (**24/C&I/18)** student of **M. Tech** (Control & Instrumentation) hereby declare that the Major Project Report titled **“CFOA Based Filter Realization”** that I am submitting to Delhi Technological University, New Delhi, in partial fulfillment of the requirement for the award of the degree of Master of Technology is an original work carried out by me. The information and data given in the report is authentic to the best of my knowledge. This report has not been previously submitted for the award of any degree, diploma, associateship, fellowship or any other similar title or prize.

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CERTIFICATE

We hereby certify that the Project Report titled **"CFOA Based Filter Realization"** which is submitted by **Pragati Sattavan (24/C&I/18)** of the Department of Electrical Engineering, Delhi Technological University, in partial fulfillment of the requirement for the award of the degree of Masters of Technology, is a record of the project work carried out by the student under our supervision. To the best of our knowledge this work has not been submitted in part or full for any Degree to this University or elsewhere.

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ABSTRACT

This thesis presents the design of an active filter using a Current Feedback Operational Amplifier (CFOA) and minimum passive components have been used (only three resistors and two capacitors). Three different filter topologies are implemented: a High Pass Filter , a Band Pass Filter , and Low Pass Filters. The circuit is designed for a cutoff frequency of 159 kHz. Performance validation is done using PSpice simulation with the AD844 model and compared with MATLAB theoretical results. Monte Carlo analysis confirms robustness under component tolerance variations. Simulation results closely match theoretical analysis, confirming the correctness of the circuit design.

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

Symbol/Abbreviation	Full Form
CFOA	Current Feedback Operational Amplifier
VFA	Voltage Feedback Amplifier
CFA	Current Feedback Amplifier
LPF	Low Pass Filter
HPF	High Pass Filter
BPF	Band Pass Filter
ASP	Analog Signal Processing
GBW	Gain-Bandwidth Product
SR	Slew Rate
ADC	Analogue-to-Digital Converter
ZT	Transimpedance Gain
CMRR	Common-Mode Rejection Ratio
PSRR	Power Supply Rejection Ratio
IoT	Internet of Things
ECG	Electrocardiography
RF	Radio Frequency
SDR	Software-Defined Radio
SAW	Surface Acoustic Wave
PCB	Printed Circuit Board
R1, R2, R3	Resistors
C1, C2	Capacitors
f_0	Cutoff Frequency (Hz)
ω	Angular Frequency (rad/s)
s	Complex Frequency Variable (Laplace)

VX, VY, VZ, VW	Terminal Voltages of CFOA
IX, IZ	Terminal Currents of CFOA

CHAPTER 1

INTRODUCTION

1.1 Introduction

Analogue signal processing involves the analogue circuit processing of continuous time and continuous amplitude signals using analogue circuits like resistors, capacitors, inductors, transistors, and op amps. In contrast to DSP which uses discrete values, ASP uses the actual continuous analog value of the quantity being processed. ASP handles all amplification, filtering, modulation, demodulation, mixing, integration, differentiation, and waveform generation operations. Such operations are generally encountered in almost all electronics used by humans when dealing with the real world in any way.

1.1.1 The Analog Signal Processing Chain

The analog signal processing block is where continuous-time is handled. The basic flow of an analog signal processing block is listed below :

- Transduction: Change physical signals to electrical signals using sensors/transducers (microphones, thermocouples, pressure sensors, photodiodes).
- Amplification: Pre-amplifiers/instrumentation amplifiers amplify the weak input signal to a strong signal, having sufficiently high Signal-to-Noise Ratio (SNR).
- Filtering: Remove noise and interference, as well as unwanted frequency components from analog signals through analog filters before processing.
- Even Signal Conditioning: Level shift/scale/linearize signal at the top if required by subsequent signal processing/stage displays. Modulation/De-modulation: In the field of communication engineering, signal modulation takes place at high frequencies of carriers, while de-modulation occurs at the receiving end.
- Analog to Digital Conversion: ADC stands for Analog to Digital Conversion. Here, the analog signal is converted into a digital signal using the ADC.

1.1.2 Applications of Analog Signal Processing

(a) Telecommunications and RF Systems

In cases where the receiver employs analog bandpass filters for receiving the desired channel by rejecting the interference from the adjacent channels, analog signal processing would be required. Analog circuits like mixers and local oscillators carry out frequency conversion while Low Noise Amplifiers are used for amplifying received weak signals while maintaining the signal-to-noise ratio. In SDR too.

(b) Biomedical Instrumentation

The current generation of medical diagnostic instruments makes heavy use of analog signal processing concepts. ECG instruments receive minute electrical waves in millivolts and filter them using analog band pass filters (0.05-150Hz) for separating cardiac rhythms from noise and other disturbances.

(c) Audio Engineering

Microphone preamplifiers amplify the input signal for further processing. The equalizers (graphic, parametric, or shelving types) employ analog filters for frequency shaping. The loudspeaker crossover employs filters for sending appropriate frequencies to speakers. Voltage controlled amplifiers are employed in dynamic range compressors/limiters, expander/noise gates after being used by an envelope follower. Analog signal processing in audio engineering demands low distortion, high fidelity and minimal noise.

(d) Industrial Instrumentation and Control

The Industrial System uses analog signal processing techniques in numerous applications such as signal conditioning in sensors, measurements of process variables, and control loops. Instruments in process control should be able to provide accurate signals related to temperature, pressure, flow rate, level, and composition. The presence of anti-aliasing filter is essential before any analog-to-digital conversion. The four to twenty mA current loop transmitters in process industries utilize precise analog amplifier circuitry. Proportional Integral Derivative (PID) controllers may be implemented using analog components such as op-amp integrator and differentiator.

(e) Radar & Sonar Systems

In both defense and commercial radar systems, complex analog signal processing operations are required for target detection and tracking, as well as for imaging purposes. Radar receivers use super-heterodyne configurations and include components such as analog mixers, IF amplifiers, and band-pass filters. Pulse compression in radars requires the use of analog delay lines or surface acoustic wave (SAW) technology. Phased-array radars require analog phase shifters and gain amplification in each antenna array elements.

1.2 Voltage Feedback Amplifiers (VFA):

1.2.1 Fundamental Architecture of the VFA

The Voltage Feedback Amplifier (VFA) or Voltage Feedback Op-Amp is the traditional operational amplifier configuration that ruled analog circuitry since the release of the μA741 in 1968. It consists of a differential input stage that calculates the voltage difference between the two inputs (noninverting and inverting), followed by gain stages and the output buffer. VFA has a high open loop voltage gain (A) of about hundred dB to 140dB (105 to 107). Negative feedback is employed to lower the gain down to precisely known and stable values according to external resistors.

1.2.2Key parameters of VFA

Performance characteristics of a Voltage Feedback Amplifier include the following parameters:

- **Open-Loop Gain (A):** Open differential voltage gain without any feedback, 105V/V or more. Such high gain allows precise regulation of the closed loop through feedback.

- **Gain-Bandwidth Product (GBW):** The most significant limitation of a VFA. The product of gain-bandwidth is a constant figure.

- **SR (Slew Rate):** The maximum rate at which the output voltage can change (V/μs). SR in VFAs depends on the charging current of the internal compensation capacitor: SR = I/C . Typical values of SR in VFAs comp are 0.5–100 V/μs.

- **Input Impedance:** The inputs have a very high impedance (bipolar: 110 MΩ; JFET/CMOS: 1012 Ω), making them suitable for connection to high-impedance signal sources.

- **Offset Voltage (V):** The difference between the two inputs that makes the output zero. Values range from several μV in precision op-amps to a few mV in general-purpose devices.

- **Common-Mode Rejection Ratio (CMRR):** The ratio of common-mode rejection capability. The typical value of CMRR in VFAs is 80–120 dB.

- **Power Supply Rejection Ratio (PSRR):** The ratio of power supply rejection capability. PSRR is usually 80–120 dB.

- **Noise:** Defined by the input-referred voltage noise density (nV/√Hz) and current noise density (pA/√Hz). Low noise VFAs have less than 1 nV/√Hz voltage noise.

1.2.3 The Gain-Bandwidth Product Constraint — A Fundamental Limitation

The gain-bandwidth product (GBW) constraint is the defining limitation of VFAs and arises from the dominant-pole frequency compensation applied to ensure closed-loop stability. To prevent oscillation in feedback configurations, a large compensation capacitor (C) is connected internally (or externally for decompensated op-amps) to create a dominant low frequency pole. This rolls off at -20 dB/decade from the open-loop gain, ensuring a phase margin ≥ 45° at the unity-gain frequency.

1.2.4 Types of Voltage Feedback Operational Amplifiers

- **General Purpose (GP) Op Amps:** LM741, LM358, TL071/TL081.Low cost, widely available. GBW 1 to 4 MHz range. Suitable for audio, sensing, and signal processing applications.

- **Precision Op Amps:** OPA177, AD707, LT1007. Offset voltage <25 µV, CMRR >120 dB. Very low-noise devices. Used in instrumentation, data acquisition systems, and metrology applications.

- **Low-Noise Op Amps:** AD797, LT1028, OPA211. Voltage noise <1 nV/√Hz. Used in preamplifier designs, medical instrumentation, and scientific instruments.

- **High-Speed Op Amps:** OPA657, LMH6702, AD8099. GBW 1 to 2 GHz, SR

1.2.5 Applications of VFA-Based Active Filters

- Sallen-Key type low-pass and high-pass filters for audio frequencies applications.
- Multiple Feedback (MFB) type Band pass filters for signals conditioning.
- State Variable (biquad) type universal filters for telecommunication purpose.
- Anti-aliasing filters for data acquisition(generally Butterworth/Bessel).

1.3 Current Feedback Amplifiers (CFA)

1.3.1 Fundamental Architecture of the CFA

The commercial availability of CFA using chips such as Comlinear CLC400 and Analog Devices AD846 in the 1980s led to the advancement of CFA into a complex and widely used technique in the field of high-speed analog circuits. The main difference between the conventional op amp and the CFA is seen in its input stage. Unlike in the case of the conventional op amp, where the input stage contains a symmetric differential pair, in the CFA, there exists a unit gain voltage buffer at the junction of its inverting and non-inverting inputs X and Y, respectively. The four terminal relationships governing CFA operation are: $V_X = V_Y$, $I_Z = I_X$, & $V_W = V_Z$.

1.3.2 Why CFA Overcomes the GBW Limitation

The transimpedance gain Z in the CFA is a function of the parasitic elements inside and is independent of the value of the external feedback resistance RF used to control the gain of the closed-loop circuit. Gain equation for the standard CFA inverter circuit is:

$$A = -\frac{R_f}{R_{in}}$$

The closed-loop bandwidth is approximately:

$$f \approx \frac{Z}{2\pi RC}$$

Where Z is the DC transimpedance and C is the capacitance associated with the transimpedance node. It is important to note that the bandwidth depends mainly on R and not on R, whose value determines the gain. As such, changing the value of R while maintaining a constant value for R will change the gain but not the bandwidth.

1.3.3 Characteristics of CFAs

- **Gain-independent Bandwidth**: Two main characteristics of a current feedback amplifier are that its bandwidth is independent of the closed-loop gain but mostly depends on the feedback resistance (RF). Thus, current feedback amplifiers can have both high gains and large bandwidth at the same time, making them very useful for high-speed applications.

- **High Slew Rate:** Since there is no limit to charging current into the compensating capacitor in current feedback amplifiers, their slew rate remains unaffected by that charge current. Therefore, CFAs can achieve the SR of hundreds to thousands of V/µs even when compared to VFAs of a comparable bandwidth.

- **Low Inverting Input Impedance:** The X terminal offers 10–100 Ω impedance. It is an inherent feature of the CFA operation but results in the low impedance of the inverting input.

- **High Non-Inverting Input Impedance:** Non-inverting input terminal (Y) offers high impedance like that in VFA.

- **Transimpedance Gain:** The open-loop gain is defined in terms of transimpedance Z (unit: V/A or Ω); T ranges from 200 kΩ to 1 MΩ at DC.

- **Voltage Supply Ranges:** Contemporary CFAs are capable of working in a supply range of ±2.5 V to ±15 V; single supply versions are possible too.

- **Distortion:** Since CFA contains an asymmetric input stage and larger quiescent currents than VFAs, then we can conclude that the distortion in CFAs will be much higher than in VFAs operating at equivalent frequencies.

- **Current Noise:** CFAs offer higher current noise levels than VFAs.

1.3.4 Applications of CFAs

The unique characteristics of CFAs make them ideally suited for applications requiring high speed and high gain simultaneously:

- Video Signal Chain Buffering/Gain: Long cable buffering and gain with controlled gain-bandwidth characteristics. The RGB chain for broadcasting and consumer video equipment employs CFA-based buffering and gain with flat response over the full video bandwidth range (5-700MHz).

- High Gain and Bandwidth Instrumentation: Oscilloscopes and spectrum analyzers need amplifier chains with gain-bandwidth performance for high gain applications.

- Communications: IF, AGC, and variable gain amplifier stages in RF/IF receivers. CATV and DSL line drivers are among them.

- Pulse Amplitude Magnifier: The high slew rate of CFAs is advantageous for radar, lidar, and particle detection pulse amplifiers.

1.3.5 Disadvantages of CFA:

- **No capacitive feedback:** The inclusion of the capacitor in the feedback loop between the output and the inverting input produces instability (the capacitor short-circuits the transimpedance at high frequencies). The all-resistive or properly compensated feedback loop must be used.

- **Critical value of the feedback resistor:** The feedback resistor R must have a certain critical value, and its value must be selected in accordance with the recommendations provided by the manufacturer (it is usually about 500 Ω-2 kΩ). Too small R reduces phase margin, while too large R reduces bandwidth.

- **Asymmetry of inputs:** Differing high input impedance in the X and Y nodes prevents using some circuitry developed for VFAs with CFAs.

- **Sensitive PCB layout:** The parasitic capacitance of the highly resistive transimpedance node Z reduces bandwidth directly. A precise PCB design is required.

- **Limited DC accuracy:** It is impossible to apply trimming techniques typical for the precision VFA circuits to the CFA input stage topology.

1.3.6 Choosing Between CFA and VFA

The selection between the current feedback amplifier and the voltage feedback amplifier totally depends on the type of applications.

Table 1.1 Comprehensive Comparison of VFA and CFA

Parameter	**Voltage Feedback Amp (VFA)**	**Current Feedback Amp (CFA)**
Gain-Bandwidth Product	Fixed GBW; BW decreases with gain	BW nearly independent of gain
Slew Rate	Moderate (0.5–100 V/µs)	Very high (500–6000 V/µs)
Inverting Input Impedance	Very high (MΩ–GΩ)	Very low (10–100 Ω)
Non-Inverting Input Impedance	Very high	Very high
Noise (Voltage)	Lower (<1 nV/√Hz achievable)	Generally higher
Noise (Current, Inv. Input)	Lower	Higher (due to low Z)
Precision / Offset Voltage	Excellent (µV range)	Moderate (mV range)
CMRR	Excellent (>100 dB)	Good (55–80 dB typical)

PSRR	Excellent (>100 dB)	Good
DC Accuracy	Superior	Moderate
Stability with Capacitive Load	Moderate (with Rs)	Sensitive; needs care
Feedback Resistor	Wide range acceptable	Critical; must be optimised
Integrator/Differentiator	Excellent (natural)	Problematic (avoid capacitive feedback)
Operating Frequency	DC to ~1 GHz (GBW limited)	DC to several GHz
Power Consumption	Low	High
Cost	Low	High
Typical Applications	Precision DC, audio, lownoise, instrumentation, filters	Video, wideband, pulse amps, ADC drivers

1.3.7 When to Choose a VFA

- When ultra-low noise operation is desired (noise <1nV/ √Hz , bias current in the range of femtoamperes)
- Where the CMRR should exceed 100 dB
- Where differential amplifiers are employed (integrators, differentiators, using capacitors in the feedback which can't be used in CFA circuitry)
- In low frequency systems (audio, DC sensing), where GBW is not an issue
- If a high impedance source is to be connected to the inverting input
- In situations demanding low power consumption with operation on a single supply of 1.8 volts
- To implement instrumentation amplifier and programmable gain amplifier circuits

1.3.8 When to Choose a CFA

- If high gain AND wide bandwidth are both needed simultaneously.
- If a very high slew rate is needed for fast pulse or transient performance
- In active filter design over a wide bandwidth (topic of this report).
- In video amplifiers and driving of cables (flat gain phase response up to 100 MHz).
- In ADC drivers, DAC buffers, and data converter interface circuitry.
- If the frequency of operation exceeds the realistic GBW capabilities of available precision VFAs.
- In transimpedance amplifiers using large capacitance photodiodes.
- In IF and RF amplifier stages where gain bandwidth capability is critical.

1.4 Current Feedback Operational Amplifier (CFOA)

Filters are essential because they are used in the various applications of analog domain. They are mostly used in communications, audio systems, and instrumentation. Conventional voltage mode operational amplifiers(VOAs) have a gain-bandwidth constraint whereby just changing the bandwidth, gain changes or vice versa . Their efficiency in high-frequency applications is limited by this fundamental constraint. For high-speed analog circuit design, CFOA has become a desirable substitute for traditional VOAs. CFOAs are perfect for wide bandwidth filter applications because they maintain constant bandwidth as compared to voltage mode operational amplifiers. Because of their high slew rate and capacity to function at high frequencies, CFOAs have become more and more popular. Simple circuit layouts and low power consumption are the results of using CFOAs for filter implementation. As a result, research efforts have focused on the design of CFOA-based filter structures that can realize several filter functions concurrently or separately. The works of Islam et al. are considered as notable contributions to this area of study. In particular, they designed mixed-mode multifunction filters based on CFOA technology in which both voltagemode and current-mode filter responses could be achieved within the same structure [12].This study highlights the capability of CFOAs to handle mixed-mode filtering operations, which is very useful in current communication and instrumentation systems. Another research was carried out by Kumar and Gupta that dealt with the design of multifunction filters with current-mode active devices where various filter characteristics such as low pass, high pass, band pass, band reject, and all-pass filters could be implemented through common structures [13].Filter design based on CFOAs of first order has also gained wide recognition especially as regards to all-pass and phase correction applications. Senani et al. have suggested two-CFOA grounded capacitor first-order all pass filter structures providing ideally infinite input impedance, which is a very important feature of cascaded filters because it avoids any loading effect between adjacent stages [11]. The above paper showed the importance of choosing proper CFOA-based structures for satisfying requirements of practical designs concerning parameters like input impedance and component grounding. Another contribution to the field of first order filter design came from Datta et al., who investigated how a single current feedback amplifier can be used in phase correction techniques for solving the practical problem of phase errors in cascaded analog signal processing systems [4]. In their later works, these authors showed the possibility of realizing high input impedance all-pass filters with one resistor, tunable gain, and minimum phase error [7]. The realization of an inverse filter using CFOA-based circuits is another noteworthy area of research. Garg et al. described a multifunction modified CFOA-based inverse filter which clearly showed that apart from being used in filters, CFOAs can be used in inverse filtering circuits that can be applied in applications like signal restoration and equalization [citation from reference list]. Maheshwari developed an approach for the tuning of first-order filters and gave an example using a current mode circuit which was generalized for CFOA-based filters to tune pole frequency [8].Circuits using two CFOAs for multi-functionality have been widely explored in the literature. Singha et al. described a multi-function circuit with two CFOAs that offered various filter outputs at the same time highlighting the significance of using a few components for providing great circuit functionality [10].The CFOA based filters are also realised in[16] and[17].

This proposed work presents two filter circuits using a CFOA one CFOA,: three resistors and two capacitors. The first circuit realizes a first-order HPF and second order BPF. The second circuit implements a second-order LPF and first order LPF. The simulation results are compared with theoretical results. Simulation results closely match with the theoretical analysis, confirming the correctness of the proposed design

1.4.1 Advantages of CFOA in Active Filter Design

The CFOA provides a number of strong benefits, particularly for the use of active filters:

- **Non-Gain Dependent Bandwidth:** Very high-gain filter stages can be designed at frequencies that are unreachable in VFAs because the filter cutoff frequencies do not depend on the gain-bandwidth product.
- **High Slew Rate:** The very high slew rate even at very high operating frequencies (2000V/μs in AD844) ensures good performance even at high signals, with no distortion due to the slew rate.
- **Z Terminal Availability:** Availability of Z terminal makes new circuit configurations feasible. The possibility of implementing multifunction filters from one integrated circuit arises through connection of an external impedance Y across terminals Z and ground, which allows separate control of transimpedance.
- **Less Passive Elements:** In comparison with filter circuits using VFAs, filter circuits employing CFOAs generally use fewer passive components, thereby reducing board space and parasitics.
- **Combined Functionality Outputs:** Simultaneous outputs for low-pass filters at V and band-pass filters at V or outputs of higher order low-pass filters can be obtained without additional active stages in one CFOA configuration.
- **Simple topology:** In this design, the universal filter uses the second-order transfer function with an extremely simple realization that only needs one CFOA, two capacitors, and three resistors.
- **Broad Dynamic Range:** Since the AD844 offers ±10 volts swing and current drive capability of ±50 mA, this ensures a good dynamic range with no distortion.

- **Compatible with Standard Circuit Analysis Methods:** Filters based on CFOAs can be analyzed by applying standard circuit analysis methods such as Kirchhoff's Current Law and Kirchhoff's Voltage Law due to their passive network RC realization.

1.4.2 CFOA Applications Beyond Filtering

Beyond active filters, the CFOA (particularly the AD844) has been extensively exploited for:

- **Oscillators:** Quadrature oscillator circuits, Wien-bridge oscillators, and phase-shift oscillators with electronic tuning capabilities for variable frequencies.

- **Immittance Simulators:** Floating and grounded inductor simulators, FDNRs, and gyrators used to realize filter prototypes.

- **Inductance Simulation:** Use of active circuits to simulate inductances and get rid of bulky inductors in radio frequency (RF) and intermediate frequency (IF) circuitry.

- **Voltage-Controlled Current Sources (VCCSs):** High accuracy sources/sinks used to bias sensors and perform analog computations.

- **Instrumentation Amplifiers:** Differential amplifiers with very high common mode rejection ratio (CMRR).

- **Phase Shifters and All-Pass Filters:** Use of phase shifters and all-pass filters in communications systems for signal conditioning purposes.

- **Analog Multipliers:** Use of four-quadrant multipliers using logarithmic-antilogarithmic approaches.

- **Waveform Generators:** Triangular waveforms, square waveforms, and sine-wave generators used

1.4.3 The AD844: Commercial CFOA Specifications

The standard CFOA ICs used like AD844 is used in research and filter design. All four terminals (X, Y, Z, W) are accessible by this IC, and can achieve innovative circuit topologies which can not be possible with standard op-amps.

Table 1.2 Specifications of the AD844 IC

Parameter	**Typical Value**	**Conditions**
Supply Voltage	±4.5 V to ±18 V	Operating range
Quiescent Current	6.5 mA	V = ±15 V S
Input Bias Current (Y terminal)	200 nA	Y terminal
Input Bias Current (X terminal)	−1.2 µA	X terminal
Input Offset Voltage	±100 µV	After trim
X-terminal Input Impedance	50 Ω	DC
Y-terminal Input Impedance	3 MΩ 2 pF	Differential
Open-Loop Transimpedance	3 MΩ	DC
Unity-Gain Bandwidth	60 MHz	R = 1kΩ f
−3 dB Bandwidth (G = +1)	60 MHz	R = 1kΩ f

−3 dB Bandwidth (G =+10)	30 MHz	R=1kΩf
Slew Rate	2000 V/µs	R = 500 Ω L
Settling Time (0.1%)	100 ns	2 V step
Output Voltage Swing	±10 V	R = 500 Ω, ±15 V supply L
Output Current Drive	±50 mA	
CMRR (DC)	60 dB	Typical
Input Voltage Noise	2 nV/√Hz	f > 1 kHz
Input Current Noise (X)	10 pA/√Hz	f > 1 kHz
Z-terminal Parasitic Capacitance	4.5 pF	
Operating Temperature	−40°C to +85°C	AD844A grade

1.5 Filters

An electronic circuit or signal processing system that allows only signals in a certain frequency band to pass through while preventing others from doing so is referred to as an electronic filter. The electronic filter is one of the basic building blocks of electrical engineering and is extensively employed in electronics. The operation of the electronic filter is fully dependent upon the frequency-dependent behavior of its elements. A capacitor and an inductor are both frequency-dependent: the impedance of the capacitor is inversely related to the frequency, while the impedance of the inductor is directly related to it. It is the frequency dependency of impedance that forms the working principle of all passive filters.

1.5.1 Need of Filters

Noise, interference, or other signals are always inherent in any practical system along with the intended signals. Filters are used to separate the desired frequencies from all others. Filters in telephones filter voice frequencies from the noise. An AM radio receiver has a filter which selects a particular station from the many stations being broadcast at the same time. Medical instrumentation uses filters to distinguish a heartbeat signal from electrical activity in the muscles.

Filters are essential in the field of communication systems. Communication would not be possible without the use of filters. Frequency-selective operation is among the most useful abilities engineers have.

1.5.2 LPF

Low Pass Filter (LPF) is a selective circuit that allows the passage of all frequency elements below a certain threshold known as the cutoff frequency (fc), with minimal or almost negligible losses, but severely attenuates all frequencies higher than fc. In theory, it can be described as a "low pass filter," which means "it passes the lows but blocks the highs." Practically, it works like this: in an RC circuit, when the frequency is low, the capacitive reactance is extremely large. There will only be a tiny amount of current flowing through the capacitor, with most of the input signal being present in the output terminal. As the frequency increases, the reactance becomes lower, with more current flowing through the capacitor, diverting the current away from the load.

1.5.3 Applications of LPF Audio

- **Engineering:** Crossover filter, Low pass filter (LPF) for Subwoofer (fc = 80 – 200 Hz) passes only the lower bass frequencies to subwoofer drivers and avoids distortion due to midrange / high frequencies in the woofer.

- **ADC/DSP:** Anti-aliasing Filter before the ADC that restricts the input bandwidth to be strictly below the Nyquist frequency (fs/2).

- **Power Electronics:** DC supply smoothing – use an LPF either using RC or LC circuitry after a bridge rectifier to obtain a smooth DC output for powering electronics.

- **Biomedical:** Processing ECG signal (with fc = 100 – 150 Hz) – to remove higher frequency EMI and muscle artifact EMG in ECG signals.

- **Control Systems:** Smoothing actuator inputs using a low-pass filter on the command signals so as to avoid high frequency chatter that may cause mechanical wear and system instability in servomotors and actuators.

- **Communications:** Root raised cosine LPF in baseband signal shaping that avoids ISI for digital signals used in modems and DSL.

- Image processing, Gaussian blur/Smoothing, Spatial low-pass filtering to reduce high-frequency noise in images (edge ringing, pixel noise).

1.5.4 HPF

A high pass filter (HPF) allows all frequencies higher than a certain cutoff frequency (fc). The HPF filters "high frequencies only while rejecting low frequencies". A resistor is used in parallel to ground and a capacitor is in series with the signal in the RC circuit. Low-frequency signals will have a high reactance ($X_c = 1/2\pi fC$) from the capacitor blocking the signal—only very little of the input is passed through to the output. When the frequency rises, the reactance drops and the signal is allowed to pass freely.

1.5.5 Applications of HPF

- **Audio Engineering**

Tweeter Crossover

HPF (fc ≈ 3–5 kHz) routes only high-frequency audio content to tweeter speakers, protecting them from low-frequency overload.

- **Amplifier Design**

AC Coupling / DC Blocking

Series capacitor (forms HPF with input impedance) blocks DC bias between amplifier stages, preventing saturation of subsequent stages.

- **Biomedical ECG**

Baseline Wander Removal

HPF with fc ≈ 0.05–0.5 Hz removes slow respiratory and movement baseline drift from ECG, preserving the cardiac waveform.

- **Image Processing**

Edge Detection & Sharpening

Spatial HPF enhances high-frequency detail (edges, textures). Laplacian and Sobel operators are 2D high-pass spatial filters. Microphone / PA

- **Rumble & Wind Noise Filter**

HPF at 80–120 Hz eliminates low-frequency mechanical vibration, handling noise, and wind rumble from microphone signals.

- **Control Systems**

PD / Derivative Action
HPF approximates differentiation — used in PID controllers to provide anticipatory phase-lead correction that improves settling time.

- **RF / Communications**

IF Stage Coupling
HPF blocks DC and low-frequency interference in RF amplifier inter-stage coupling networks in receivers and transmitters.

- **Seismology**

P-wave Extraction
HPF separates high-frequency primary (P) seismic waves from slow-moving, highenergy surface waves in seismograph recordings.

1.5.6 BPF

The Band Pass Filter (BPF) allows only a selected band of frequencies to pass through the filter circuit. It is characterized by the lower cut off frequency (f1) and higher cut off frequency (f2). It filters out the signal outside the selected band of frequencies. The BPF can be thought of as a combination of high pass filter and low pass filter. The High Pass Filter (HPF) is used for setting up f1 and the Low Pass Filter (LPF) is used for setting up f2 where f1<f2. Thus HPF filters out the signals below f1 and LPF filters out the signal above f2. Therefore, only that part of the signal which lies between f1 and f2 can pass through.
Practically, BPFs use RLC resonant or second order active filters because they exhibit natural characteristics of band pass..

1.5.7 BPF Applications

- **Reception of radio and television broadcasts**: The primary role of a bandpass filter in a radio receiver is that of a selective filter for a chosen narrow frequency channel out of the broad range of possible signals within the broadcast spectrum. The tuned frequency fo in an AM radio will correspond to the carrier frequency of a particular radio station (for example, 810 kHz), with the bandwidth of about 10 kHz (the width of the broadcast channel). Other radio stations are filtered out.

When tuning the receiver, you actually adjust the capacitance in the tank circuit, thereby adjusting the tuned frequency fo to select different radio stations.

- **Telephone keypad decoding (Touch-Tone):** Pressing a particular key on a telephone keypad generates two tones at once. For example, the key "5" will produce both 770 and 1336 Hz signals. The telephone central office decodes those tones by using an array of band-pass filters – each tuned to one of the eight possible frequencies of the DTMF signaling system (697, 770, 852, 941, 1209, 1336, 1477, and 1633 Hz).

- **Audio Graphic Equalizer:** The Audio Graphic equalizer splits the sound range in octaves or in 1/3 octaves bands, with each band being formed using a BPF (peaking filter). Some bands include 31.5Hz, 63Hz, 125Hz, 250Hz, 500Hz, 1KHz, 2KHz, 4KHz, 8KHz, and 16KHz. The user adjusts each individual band either up or down, shaping the whole sound profile.

- **EEG brain waves analysis:** Electroencephalogram is an instrument that measures the brain electrical activity. In accordance with different states of consciousness or nervous activity there are five types of brain waves: delta waves (0.5-4Hz for deep sleep), theta (4-8Hz for drowsiness and memorizing), alpha (8-13Hz for relaxed alertness), beta (13-30Hz for active thought) and gamma (30-100Hz for concentration).

- **Intermediate Frequency (IF) stage in Super Heterodyne receivers**: Almost all radio receivers have the input signal mixed or multiplied with a signal from the local oscillator to generate an intermediate frequency (IF). For example, an intermediate frequency for AM radio is 455 kHz, while for FM radio it is 10.7 MHz. A highly selective BPF having a fixed frequency makes the circuit selective. The heterodyne technique enables the bandpass filter to work at a constant frequency irrespective of the band width.

1.5.8 BSF Definition and Concept

A Band Stop Filter (BSF), which can also be termed as Band Reject Filter or Notch Filter, is just the reverse of a Band Pass Filter. While a BPF transmits a band of frequencies and rejects all others, the BSF will block a particular band of frequencies but will transmit all the frequencies both above and below that band of frequencies.

This particular band of frequencies that is stopped is bounded by a lower cutoff frequency of f1 and an upper cutoff frequency of f2. The center frequency of this band would be given by fo = √(f1 × f2) and the bandwidth would be equal to the difference in the frequencies f2 – f1.

The name notch filter is reserved for those extremely narrow band stop filters, which have a high value of Q and produce a deep notch in the frequency response spectrum centered around one frequency only.

1.5.9 The key distinction:

- Wide BSF (low Q): rejects a broad band — used for interference band removal.
- Narrow notch filter (high Q): rejects one precise frequency — used for specific tone elimination.

1.5.10 Applications of BSF

- **Power-Line Hum Rejection (50/60 Hz Notch)**
  Most common usage. Power lines generate electromagnetic disturbances at 50 Hz (India, Europe, world over) or 60 Hz (America, Canada). The hum noise finds its way into sensitive measuring instruments, audio equipment, and biometric devices due to ground loops, inductive coupling, or capacitive coupling. A notch filter with resonance frequency fo accurately tuned to 50 Hz or 60 Hz removes this disturbance without altering the desired signal. For ECG and EEG instruments and EMG machines, a 50 or 60 Hz notch filter is a requirement. The value of Q is maintained high enough to remove hum and yet low enough not to cause ringing in transients — generally, Q = 10 to 30.

- **Audio Feedback Elimination (PA Systems)**
  In PA systems and live audio reinforcement applications, acoustic feedback is caused by the microphone picking up the sound emanating from the speaker, which is then amplified and emitted to cause that well-known piercing squealing noise. Acoustic feedback occurs when the gain in a particular frequency exceeds unity. An auto-feedback suppressor employs several narrow notch filters (equalizers). Whenever there is a feedback problem at a certain frequency, that frequency's signal is filtered out through placing notches, thereby lowering its gain below the feedback point.

- **Interference Rejection in Radio Communications**
  In radio receivers, if there is interference from a neighboring transmitter that uses an adjacent frequency, the receiver can get overloaded due to this interference. In such a case, a BSF is employed in the signal path ahead of the mixer, and this blocks the interference signal. This is usually the case with military and emergency communications that operate in a crowded frequency band.

- **EMG (muscle signal) processing:** Motion artifact rejection - electrode movement creates a low-frequency spike; a notch filter attenuates it but does not destroy the muscle signal.

- **Implantable devices -** Pacemakers have notch filters for eliminating self-generated stimulus pulses from being misread by the device as normal heart signals (both blanking and notch filtering are used).

- **MRIs** - RF artifacts due to gradient coil switching at certain frequencies are notch filtered from MRI data streams.

1.5.11 Comparison of Low-Pass, High-Pass, and Band-Pass Filter Characteristics.

Table 1.3 Comparison of Low-Pass, High-Pass, and Band-Pass Filter

Parameter	**Low-Pass Filter**	**High-Pass Filter**	**Band-Pass Filter**
Passes	Frequencies below f_c	Frequencies above f_c	Frequencies between f_1 and f2
Attenuates	Frequencies above f_c	Frequencies below f_c	All frequencies outside the band
Cutoff Points	One upper cutoff f_c	One lower cutoff f_c	Two: f_1 (lower), f_2 (upper)
Center Frequency	Not applicable	Not applicable	$f_o = \sqrt{(f_1 \times f_2)}$
Transfer Function (1st Order)	$\omega_c / (s + \omega_c)$	$s / (s + \omega_c)$	$(\omega_o/Q)\cdot s / (s^2 + (\omega_o/Q)s + \omega_o^2)$
Roll-Off (1st / 2nd Order)	−20 / −40 dB per decade	−20 / −40 dB per decade	−20 / −40 dB per decade each side
Quality Factor Q	Not applicable	Not applicable	Q = f / BW — key selectivity parameter
Simplest Passive Circuit	RC (R series, C to GND)	CR (C series, R to GND)	Series or parallel RLC
Key Active Topology	Sallen-Key LPF	Sallen-Key HPF	Multiple Feedback (MFB) BPF

Typical Applications	Anti-aliasing, noise reduction, audio bass	AC coupling, ECG, edge detection	Radio tuning, EQ bands, EEG

1.6 Conclusion

The basics of analog signal processing as well as the basic components have been explained in this chapter. The working principle of Voltage Feedback Amplifiers (VFA) and Current Feedback Amplifiers (CFA) along with some essential details on how they differ from one another was described. Whereas VFAs provide great precision and low-noise performance, CFAs get rid of the limitation that exists in terms of gain-bandwidth with the help of slew rate and gain-independent bandwidth. The Current Feedback Operational Amplifier (CFOA), in particular, the AD844, is presented as an excellent active device that can be used to build filters because of its broad bandwidth and high slew rate as well as the possibility to access any terminal of it. Four types of basic filters – low-pass, high-pass, band-pass, and band-stop – have been introduced.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Since the eighties, interest has been shown in designing active filters utilizing current feedback operational amplifiers (CFOAs) due to the intrinsic bandwidth limitation of the voltage feedback amplifiers (VFA) in achieving high-frequency and high-gain conditions. The contributions made to CFOA-based filter design, current-mode active filter realization, immittance simulation, oscillator design, and other related analog signal processing areas have provided direct motivation and insight into the current work.

2.2 Fundamental Research on CFOA-Based Filter Design

The fundamental research work on designing active circuits utilizing CFOA has been presented in the definitive text book by Senani, Bhaskar, Singh, and Singh, where the port relations VX = VY, IZ = IX, and VW = VZ, have been clearly stated and a detailed classification of various CFOA-based filters, oscillators and immittance simulators has been introduced [18]. This paper provides the theoretical foundations for understanding the benefits of using CFOA over VFA and is thus a theoretical cornerstone for the current effort.

In their analysis, Chen and Zhong synthesized methodologies for high pass, bandpass and low pass filters based on CFOA and were able to derive the transfer functions straight from the CFOA port equations and further used them in designing quadrature oscillators using the same structure [14]. This synthesis is clear evidence that the multi-function filters can be realized utilizing the W-terminal buffered output and Z-terminal high impedance terminal without any additional active element.

Kumar et al. further developed two-CFOCFOA based topologies that would realize all the popular filter responses using grounded capacitors, hence simplifying the construction process of the PCB and mitigating parasitic effects through a filter structure realized in designing the first order universal active filter [19]. It is evident that this extension methodology is the pathway to the universal filter implementation, which is the main objective of the future research in the current project.

2.3 Mixed-Mode and Multi-Function CFOA Filters

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2.4 Current-Mode Active Filter Design

There is a lot of research on realizing active filters through the use of current-mode active elements, in which the variables of the signals used are expressed by their currents rather than their voltages. In their study on designing multi-function active filters through the use of current-mode active elements, Kumar and Gupta proved that current-mode designs provide higher dynamic range and better high frequency operation compared to voltage-mode designs at the same supply voltage [2].

designs of the current-mode first-order universal filters are made possible by the efforts of the Chaturvedi, Mohan, and Kumar. In 2019, a new model of a current-mode first-order universal filter was proposed by the group. This was followed by the development of a low voltage filter applicable to battery-operated systems and another filter that can be electrically controlled. A current CFOA-free f a first-order current-mode filter that requires no resistive tolerances at all was made possible by the group in 2020.

To allow a full integration of CMOS realization, Agrawal and Maheshwari proposed an active-C current mode universal first-order filter and oscillator, which required the use of active devices only and had ground-referenced capacitors but no resistors. Maheshwari developed a systematic method of tuning for first order filters, and provided a unique example of current mode filter, which demonstrated the procedure of tuning pole frequency independently while maintaining the nature of filter unchanged. In order to demonstrate the multiple uses of filter circuits as oscillators, Kumar and Paul utilized a combination of current mode first-order universal filter and multiphase sinusoidal oscillator in the same topology. This approach has direct relevance to oscillator applications discussed in Chapter 1 of the present thesis.

Ansari and Soni proposed digital control of filter coefficients in place of analog tuning by implementing digitally programmable differential current mode first-order LP, HP and AP filter sections.

2.5 Electronically Tunable Filters and Immittance Functions

For adaptive and reconfigurable signal processing circuits, the facility of electronically controlling the parameters of active filters is important. Recently, an electronically tunable resistorless first-order universal filter using an ICCII (Inverting Second Generation Current Conveyor II) based technique was reported by Safari, Yuce, and Minaei. The new technique involves modulating the cutoff frequency of a filter by employing a bias current in absence of any passive resistor.

Voltage-controlled RC networks connected with the Z terminal of the CFOA have been shown to be useful for the generation of electronically tunable dual-input integrators and realization of synthetic immittance function [5] by Mathur, Pattanayak, and Nandi. An interesting property of the CFOA is its Z-terminal tunability. In other words, a CFOA offers a circuit configuration beyond standard op amps and provides the base for designing tunable filters in the future.

The work carried out by Mathur, Pattanayak, and Nandi regarding the electronically tuneable dual input integrators and synthesis of immittance functions using CFOAs [5] proves the possibility of making an adjustable pole frequency using a voltage controlled RC network connected to the Z terminal of the CFOA. It is the unique capability of CFOAs whose circuit configuration surpasses conventional op-amp circuits that forms the basis of the proposed filter extension design project.

2.6 Synthetic Inductors and Capacitance Multipliers

Simulation of passive reactive components such as inductors and capacitance multipliers becomes a significant area of study in filter design at higher frequencies where real inductors may not be available. Yucean & Yuce presented a grounded capacitance multiplier that precisely tuned the value of equivalent capacitance using a grounded capacitor and a single ICFOA [12]. Besides Mehrotra's approach using VCI, this capacitance multiplication method can directly apply to our current circuit to decrease the BPF center frequency without increasing the value of any physical capacitor [8].

Yuece and Minaei developed a novel active component known as SCCI (Second Generation of Current Conveyor variant) and applied it in simulations of floating inductors and quadrature oscillators [11]. Another recent configuration for grounded series lossy inductor using OTRA as the basic block was suggested by Mann, Kumar and Bhaskar [13]. This is an addition to the growing list of inductor simulation circuits that eliminate the need for any inductor in filter circuit design. Filter and quadrature oscillators designed using current conveyors employing only grounded capacitors and resistors were suggested by Horng [17].

As shown by Gupta et al., low-voltage grounded inductors can be obtained by using the MOS-C model with pairs of sub-threshold biased MOSFETs at very low voltages, down to 0.5V, through the development of a low-voltage grounded synthetic inductor based on the DTMOS circuit [6]. Considering our applications for the Internet of Things and wearable bio-medical devices described in Chapter 1 of this thesis, our inductor simulation method becomes necessary.

2.7 All-Pass Filters and Phase Correction Circuits

Applications of all-pass filters include phase equalization, delay of signals, and generating quadrature signals. In an all-pass filter, there is a phase difference that varies with frequency, whereas unity gain is constant throughout the frequency range. The current conveyor, suitable for use as a basic block to realize phase-shifting circuits, was determined by Salawu from his study of the all-pass transfer function realization using a second generation current conveyor (CCII) [16].

All-pass networks based on CFA technique have been reported to be able to provide phase accuracy better than 1° over a wide frequency band [9], as shown by the work of Datta, Venkateswaran, and Nandi showing a design of a high input impedance, single resistor adjusted variable gain all-pass filter having low phase error implemented through the use of current feedback amplifier. In a subsequent paper, Datta et al. showed through phase correction circuits involving single current feedback amplifier that just one active device is sufficient for phase equalization [7]. It is clear that such an extension of all pass filter discussed in section 6.5 of this thesis is possible.

2.8 Oscillators and Nonlinear CFOA Applications

Closed loop poles placed along the imaginary axis due to regulated positive feedback will turn the same RC network utilized in filters into a sinusoidal oscillator. The dual utilization of filter structures to serve as oscillators was shown by Beg et al., who showed how the four-phase sinusoidal oscillator and multioutput filter structure can be realized by using MOSFET transistors [20]. Chapter 1 of the present research, which focuses on CFOA-based quadrature oscillator designs as a natural progression from the filter circuits, is relevant to this concept.

With the help of a CCCFA (Controllable Current Conveyor based Current Feedback Amplifier), Shukla and Paul developed a three dimensional autonomous chaotic oscillator, proving the utility of the CFA family circuits in nonlinear dynamic and secure communication applications [10]. This application shows how versatile the CFOA is, albeit not directly related to the linear filter design presented here.

2.9 Recent Advances in First-Order Universal Filter Design

Recent developments have seen significant advances in the design of first order universal active filters due to their ability to solve limitations faced in traditional designs by introducing novel circuit blocks, ultra low voltage circuits and re-configurable multi-mode topologies. The authors Dogan, Yuce, and Minaei advanced the development of the CFOA-based first order voltagemode universal filters using CFOAs [48] in an extension of previous research that introduced new high-frequency filter topologies from fundamental concepts. Further on, in a subsequent publication by the same authors, first order universal filters utilizing two CCII+ blocks and one grounded capacitor were designed and verified experimentally [31].

On the other hand, Alpaslan showed that the CFOA-based topologies can systematically be generalized to higher-order topologies and multi-input arrangements with preservation of the gain-bandwidth product independence characteristic of current feedback configurations through the use of a second order mixed-mode multi-input single-output universal filter circuit employing three CFOA blocks in the design of mixed-mode filters [34]. Taray and Kumar introduced a first order mixed-mode universal filter with gain control capability employing a CMOS DX-CCII block proving the growing importance of purpose-built active circuits for reconfiguration [32].

The rapid proliferation of wearable devices, battery operated gadgets, and the Internet of Things technology has spurred much interest in the design of filters that require low-voltage and operate at the nano power level. The contributions of Khateb, Kumngern, and Kulej in this field include a voltage-mode firstorder universal filter at 0.5V using multiple input OTA [50], and a voltage-mode first order analog filter at 0.3V, 357.4 nW using multiple input VDDDA [49]. Both contributions prove the possibility of achieving sub-volt and nanowatt operation while maintaining filter universality. Building further on the low-voltage design concept, Kumngern, Khateb, and Kulej have proposed a voltage-mode versatile first-order analog filter at 0.3 V using multiple-input DDTAs [46], and a lowvoltage mixed-mode analog filter using multiple-input multiple-output

OTAs [41], which marks an important step towards ultra-low-voltage multimode filters and has relevance to the applications described in Chapter 1.

By proposing a multimode first-order universal filter cell that uses voltage conveyors (VCIIs) to achieve simultaneous voltage-mode, current-mode, and transadmittance-mode operation from a single compact topology without circuit reconfiguration, Buakaew and Silaruam further demonstrated the adaptability of first-order filter topologies across multiple operating modes [33]. This multimode reconfigurability without structural modification is consistent with the design philosophy used in the present work, where HPF and BPF responses are generated from a single CFOA topology by repositioning passive components at the input stage.

To address the practically important problem of frequency control accuracy in the context of integration when the absolute component values can be changed due to process variation, Nako, Psychalinos, and Minaei proposed the designs of first-order universal shadow filters with scaled time constants [40].The research is also relevant to the Monte Carlo robustness analysis conducted for the designs of this chapter in Chapter 6 of this project.

Concerning the area of current mode filter design, Kumngern et al. proposed a first-order versatile filter realized in one EXCCCII [38], while Kumngern et al. suggested another versatile filter with controlled current gain [47].Their research supports the existing tendency towards electronically controllable filters with one active device and minimum number of passive elements, an approach that is followed in the present project.

The design of current-mode active filters made up of CCCII elements tailored for biomedical signal processing by Zahiruddin et al. [35] and the 0.5 V mixed-mode universal active filter based on multiple-input OTAs suitable for portable and biomedical instruments developed by Phatsornsiri et al. [39] are two instances of contributions targeting specific applications. Such application-driven designs support the motivation given for biomedical and instrumentation uses of universal filters in Chapter 1 of this thesis and prove that universal filter topologies have wide practical utility outside laboratory experiments.

As regards reduction of passive components, Yucehan developed lossless grounded capacitance multipliers requiring just two CFOAs and a grounded capacitor [36]. This solution is an immediate extension of the capacitive multiplier approach discussed in Section 1.7.5 and offers a feasible method to lower filter corner frequency values without increasing the capacitance value of the corresponding capacitors. This solution is useful for the BPF architecture adopted in this project. The contribution from Yadav, Bansal, and Senani introduces a new electronically fine tunable CMOS floating resistor structure [37]. Such a circuit represents a building block that may be helpful in implementing electronically tunable filters, as suggested as a further development of this project.

In addition, Raj et al. expanded the list of single active element filters by proposing a first-order VM/TAM universal filter circuit using only a single differential difference current conveyor with practical applications [43]. Similarly, Kaharwar et al. showed that it is possible to design a first-order universal active filter circuit using only a single VCII+ configuration and prove the ability to implement a variety of responses of low pass, high pass, band pass, and all-pass simultaneously in an active filter using a single active element along with a few passive elements [45].

First order filters' double duty as signal processors and sinusoidal oscillators is illustrated by Kumar and Kushwaha's two related contributions. In their works, Kumar and Kushwaha proposed a cascaded all-pass filter and a new current mode first order filter with oscillation capabilities from the same FDCCII based configuration [42], [44].

References [31] to [50], on the other hand, collectively demonstrate that research into universal active filters of the first order continues to be an exciting and highly prolific research field, involving active research efforts in various areas such as ultra-low voltage CMOS realization, reconfigurable multi-mode architectures, electronically tunable filters, application-specific biomedical implementation, and even methods for eliminating all passives in active filters. The current feedback operational amplifier-based filter topology discussed in the present work, which features a miniaturized, wideband and multi-purpose filter configuration making use of the architectural strengths of CFOA topology to achieve required specifications, belongs to this broader field of research as well.

2.10 Coclusion

This chapter provided an overview of the existing literature on CFOA-based active filter design and analog signal processing circuits. Fundamental CFOA-based filter circuit configurations along with mixed mode, multi function filter designs, current mode active filter design, electronically tunable filters, immittance simulation, all pass filters and oscillators have been covered in the survey. From the literature review, it is clear that CFOAs provide certain advantages compared to the VFAs owing to their gain independent bandwidth, fast slewing capability and flexible terminal access. Recently, a new approach towards designing first order universal filters has emerged and it reflects the trend towards reconfigurable, low voltage and application specific filter configurations. Identification of shortcomings and methodologies in design philosophy revealed from the above discussion motivates the design of CFOA based filter circuits presented in the next chapters which aim at achieving various filter responses simultaneously using only one CFOA.

CHAPTER 3

PROPOSED CIRCUIT DESCRIPTION AND ANALYSIS

3.1 Introduction

The Symbolic Representation of CFOA is shown in Figure1. The current feedback operational amplifier has four terminals (X, Y, Z and W). Y terminal high input impedance, X terminal low input impedance , Z terminal high output impedance and W terminal low output impedance . The terminal characteristic equations of Current feedback operational amplifiers are :

$I_Y=0$, $V_X = V_Y$, $I_Z = I_X$, and $V_W = V_Z$.

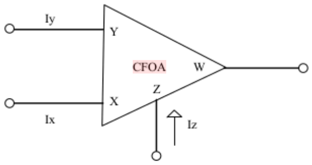

Fig. 3.1 Symbolic representation of CFOA

3.2 Circuit Configuration

Fig.2 below shows the general CFOA-based filter topology used in this work. The circuit employs a single CFOA with three resistors (R_1, R_2, R_3) and two capacitors ($C_1$and C_2). In the given figure Y_1 is R_1parallel to C_1. The versatility of this configuration allows for multiple filter responses by simply rearranging the positions of R_2 and C_2 at the input stage.

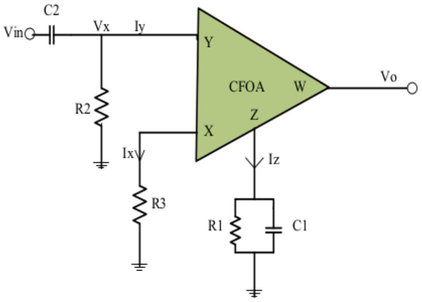

Fig. 3.2 Proposed Filter configuration to realize First-order HPF and Second-order BPF

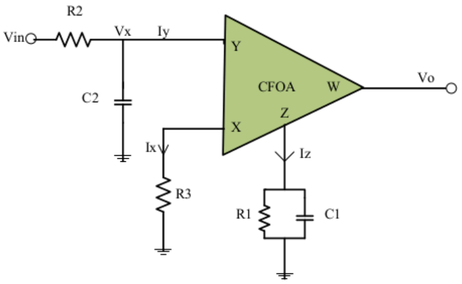

Fig.3.3 Proposed Filter configuration to realize First-order LPF and Second-order LPF

The routine analysis of the circuit shown in Fig. 3.3 results following is the Transfer Function

$$\frac{V_{OS}}{V_{IN}} = \frac{sR_2C_1}{s^2 + s[\frac{1}{R_1C_1} + \frac{1}{R_2C_2}] + \frac{1}{R_1C_1R_2C_2}]} \qquad (1)$$

Which is a second-order BPF with cutoff frequency :

$$\omega_O = \frac{1}{\sqrt{R_1C_1R_2C_2}}$$

and Pass Band Gain (Ho) = 1. In the same configuration if we select input at node Vx the filter response is as:

$$\frac{V_{XS}}{V_{IN}} = \frac{sR_2C_2}{sR_2C_2 + 1} \qquad (2)$$

Which is a first-order HPF with cutoff frequency:

$$\omega_O = \frac{1}{\sqrt{R_2C_2}}$$

and Pass Band Gain (Ho) = 1. Similarly if we realise the circuit of fig.3.3 the responses are as:

$$\frac{V_{XS}}{V_{IN}} = \frac{1}{1 + sR_2C_2} \qquad (3)$$

$$\frac{V_{OS}}{V_{IN}} = \frac{\frac{1}{R_1C_1R_2C_2}}{s^2 + s[\frac{1}{R_1C_1} + \frac{1}{R_2C_2}] + \frac{1}{R_1C_1R_2C_2}]} \quad (4)$$

Which are first order LPF and second order LPF with Pass Band Gain (Ho) = 1and cutoff frequencies:

$$\omega_O = \frac{1}{\sqrt{R_2C_2}}$$

$$\omega_O = \frac{1}{\sqrt{R_1C_1R_2C_2}}$$

3.3 Conclusion

In this chapter, we have discussed the suggested CFOA-based filter circuits together with its theoretical analysis. There are two types of filters presented, each consisting of a single CFOA with three resistances (R1, R2, R3) and two capacitances (C1 and C2). The first circuit provides a first-order HPF response and a second-order BPF response, whereas the second one offers a first-order LPF response and a second-order LPF response with just the re-positioning of R2 and C2 to the input side.

The transfer function equations for all four filters have been deduced using conventional circuit theory with the help of the CFOA port conditions. The simplicity in terms of fewer active and passive devices leads to an elegant circuit architecture. The above theoretical analysis shows that multiple filter responses can be obtained through one single CFOA structure. This chapter will be followed by the simulation results in the next chapters.

CHAPTER 4

SIMULATION AND THEORETICAL RESULTS

4.1 Introduction

The circuit's simulated using PSpice with the macro model of AD844 All filter responses are designed for a cutoff frequency of 159kHz with circuit parameters as shown in Table 4.1.

4.2 Parameter and Simulation Cutoff Frequency

TABLE 4.1 PARAMETER SELECTIONS

S. No.	Components	Values
1.	Resistor (R_1)	1 kΩ
2.	Resistor (R_2)	1 kΩ
3.	Resistor (R_3)	1 kΩ
4.	Capacitor (C_1)	1 nF
5.	Capacitor (C_2)	1 nF

Table 4.2 shows the theoretical and simulated cutoff frequencies of the filters of Fig. 3.2 and Fig. 3.3

TABLE 4.2 THEORETICAL CUTOFF FREQUENCY

S. No.	Filters	Theoretical Cutoff Frequency	Simulation Cutoff Frequency	% Error
1.	BPF	159 kHz	157.9 kHz	1.10%
2.	HPF	159 kHz	158.3 kHz	0.44%
3.	LPF	159 kHz	156.8 kHz	1.38%

4.2 Simulation Results

The circuit's performance is validated using PSpice with the AD844 model. The simulated (Simulation) and MATLAB (Theoretical) frequency responses have been compared and demonstrated in the figures below.

4.2.1 Gain Results

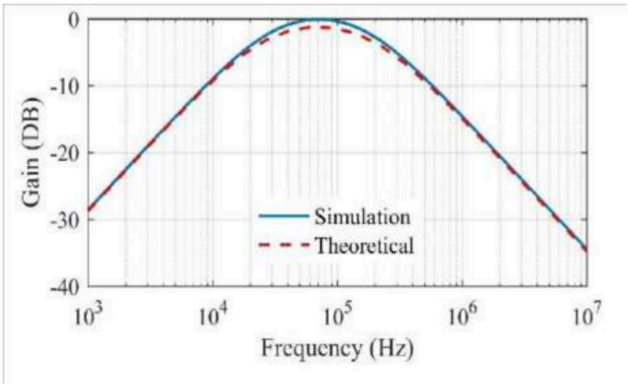

Fig.4.1 Frequency Response Of Band Pass Filter

From the output of the Band Pass Filter, it can be seen that the gain begins from about -40 dB at low frequencies (10^3 Hz), increases linearly to reach its maximum value at 0 dB near the centre frequency of 10^5 Hz, and then declines back down to -40 dB for high frequencies (10^7 Hz). The two lines representing the simulation (solid blue) and theoretical (dashed red) values coincide within the passband region.

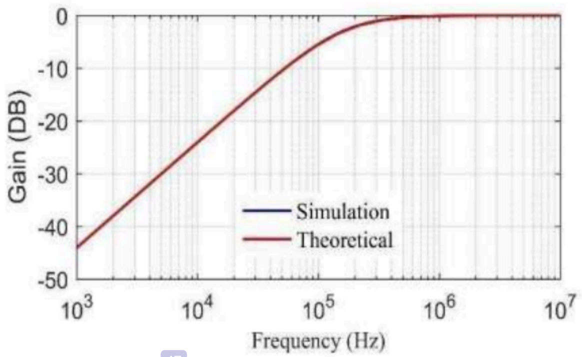

Fig. 4.2 Frequency Response Of High Pass Filter

From the high pass filter output graph, the gain starts at −50 dB at 10^3 Hz and rises steadily with increase in frequency to reach 0 dB flat gain at 10^5-10^6 Hz. The theoretical curve matches perfectly with the simulation curve; hence, the filter performs very well by filtering out low frequencies and passing the high frequencies.

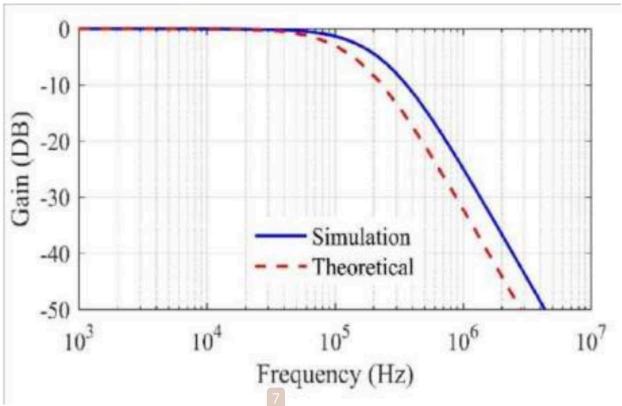

Fig. 4.3 Frequency Response Of Low Pass Filter

From the above output of the low pass filter, the gain is almost constant for a flat response in the passband ranging from 10^3Hz up to about 10^5Hz before it sharply drops, achieving about -50dB at 10^7Hz. The simulated response and theoretical calculations agree very well until the point where the response becomes sharp, a difference that arises due to the real performance of AD844.

4.2.2 Phase Results

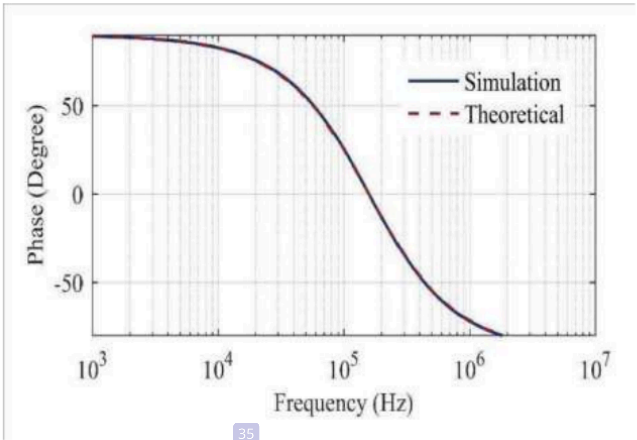

Fig. 4.4 Phase Response Of Band Pass Filter

The band pass filter phase response starts at about +70° in the lower frequency range (10^3 Hz), is relatively flat and gradually changes through 0° at the centre frequency of about 10^5 Hz, to finally reach about −70° in the higher frequency range (10^6-10^7 Hz). It can be noted that the simulation curve and theoretical plot match each other very well throughout the entire frequency range.

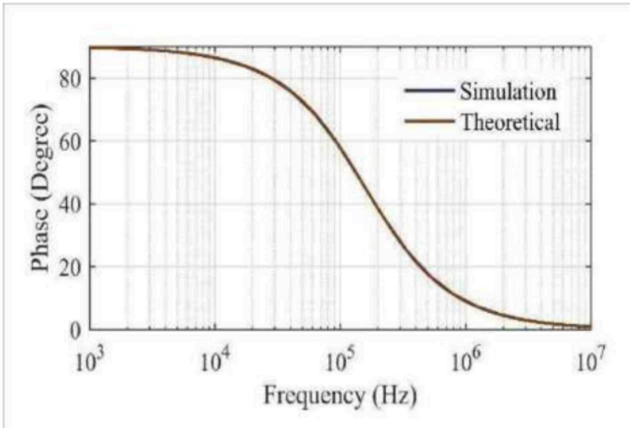

Fig.4.5 Phase Response Of High Pass Filter

As far as the phase characteristics of the high pass filter is concerned, the value of the phase at which the response starts is quite high, almost equal to 80 degrees at the lower end of frequency value (10^3 Hz), but then goes on decreasing as the frequency value increases, reaching close to zero at frequencies more than 10^6 Hz.

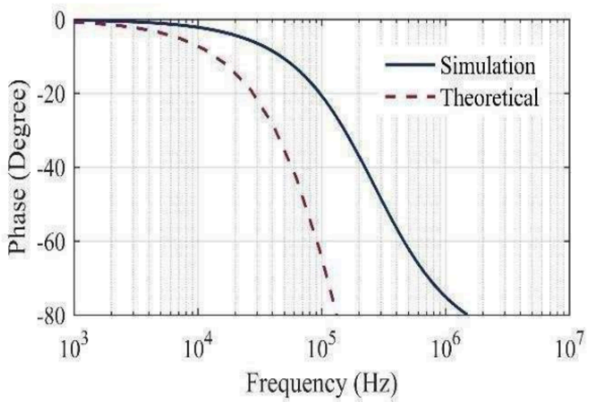

Fig.4.6 Phase Response Of Low Pass Filter

The phase shift of the low pass filter starts from 0° at lower frequencies and then drops linearly, ending up at around -80° at high frequencies greater than 10^6 Hz. There is a small difference between the simulated curve (solid line) and theoretical curve (dashed line) that can be seen in the range of 10^4 – 10^5 Hz, caused by the parasitic behaviour of AD844 CFOA in this frequency range.

4.2.3 The Monte Carlo Analysis

Monte Carlo analysis has also been carried out with 10% variation in resistor and 5% variation in capacitor with hundred simulation runs.

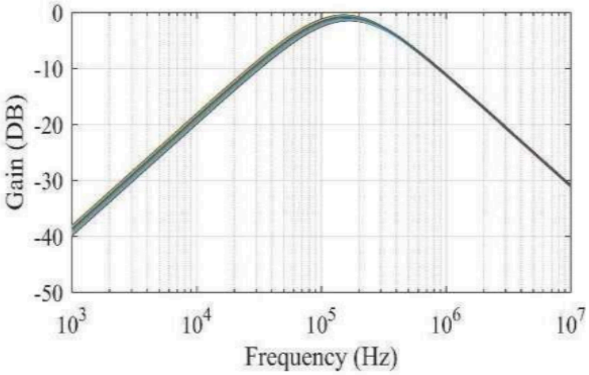

Fig.4.7 Variation in frequency response with 10% variation in resistor and 5% variation in capacitor for Band Pass Filter .

From the results obtained using Monte Carlo analysis for the Band Pass Filter circuit, a series of gain graphs are obtained whose centre frequency is approximately 10^5 Hz and the maximum gain is near 0 dB. This is achieved through a range of simulation processes which result in a graph showing a series of gain curves which all possess the bell shape characteristic frequency response and roll-offs on either side. It can be noted that the range of gain graphs is fairly narrow through the pass band region.

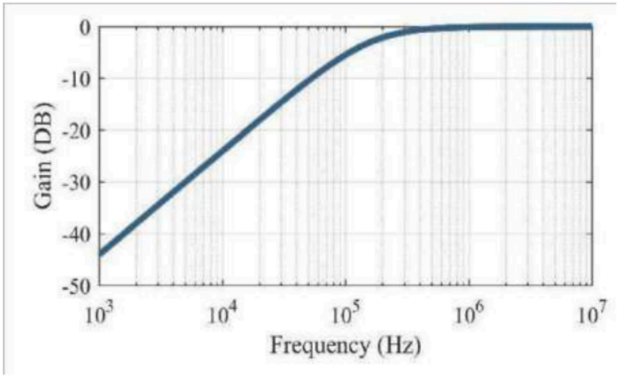

Fig.4.8 Variation in frequency response with 10% variation in resistor and 5% variation in capacitor for High Pass Filter.

Result of high pass filter obtained through Monte Carlo analysis displays all the curves from the simulation runs clustered around each other, following the same increasing response with respect to frequency. The gain increases from about −50 dB for 10^3 Hz frequency and flattens to 0 dB in the passband region above 10^5 Hz. The tight clustering of the curves indicates that the high pass filter is stable and insensitive to the variations in the components used.

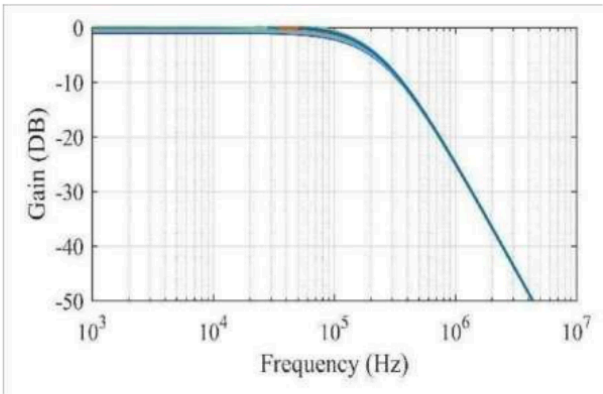

Fig.4.9 Variation in frequency response with 10% variation in resistor and 5% variation in capacitor for Low Pass Filter.

Similar results in terms of gain stability are obtained in the case of the low pass filter using the Monte Carlo method. Specifically, a stable value close to 0 dB is observed within the passband from 10^3 Hz to 10^5 Hz, after which a roll-off occurs. Indeed, the results of the 100 Monte Carlo iterations lead to closely spaced graphs with minimal deviation at all frequencies. In summary, the Monte Carlo study indicates the ability of all three filters (band pass, high pass, and low pass) to tolerate variation in their components.

4.2.4 Histogram Results

The histograms were analysed from 100 runs to assess statistically the distribution of the centre/cutoff frequencies of the filter design under component tolerances.

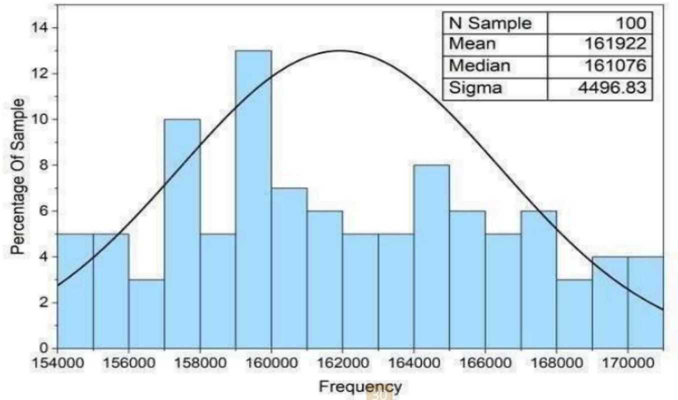

Fig.4.10 Histogram Result Of Second Order Band Pass Filter

The histogram for the second order band pass filter shows the centre frequency distribution for 100 simulation runs, where statistical results can be summarized as:

- N Sample: 100
- Mean: 161,922 Hz
- Median: 161,076 Hz
- Sigma (σ): 4,496.83 Hz

The distribution ranges roughly from 154,000 Hz to 170,000 Hz, where the greatest number of samples occur in the range of 160,000 Hz and 164,000 Hz accounting for 13% of the total sample population. From this plot, we can see the bell-shaped distribution curve superimposed by a Gaussian normal curve, thus validating that the variation of the centre frequency follows the Gaussian distribution. The low value of the standard deviation (sigma) of 4,496.83 Hz indicates good stability of the centre frequency within the band pass filter.

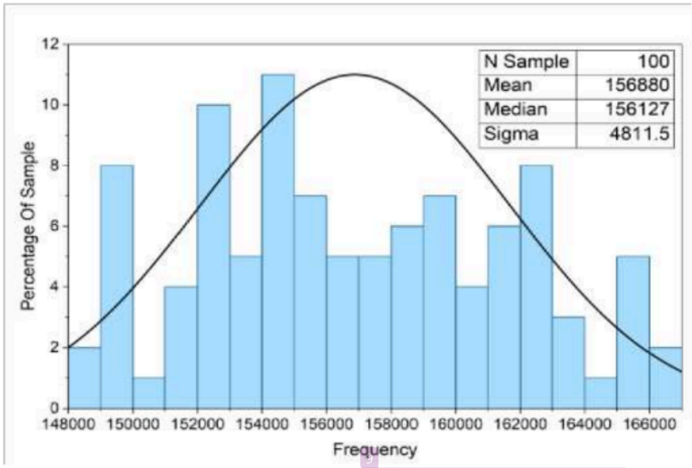

Fig.4.11 Histogram Result Of Second Order Low Pass Filter

Histogram of the second order low-pass filter represents the frequency distribution of cutoff frequencies of 100 simulations as shown below:

- Sample Size (N): 100
- Mean: 156,880 Hz
- Median: 158,127 Hz
- Standard Deviation (σ): 4,811.5 Hz

It goes from about 148,000 Hz to 166,000 Hz with data somewhat more scattered than the band pass filter. The normal distribution overlay graph depicts a fairly Gaussian distribution. The sigma value for it, however, comes out to be 4,811.5 Hz, which is slightly larger than that of the band pass filter, thus making it slightly more sensitive to changes in component values.

As expected, both graphs show that these designs do yield statistically uniform results after a total of 100 Monte Carlo simulations, since frequency distributions are close to a normal distribution and sigma is fairly small relative to the mean frequency.

4.3 Conclusion

The analysis and simulation results of the developed CFOA-based filter circuit designs using AD844 macro model in PSpice have been discussed in this chapter. All three filters Band Pass Filter, High Pass Filter and Low Pass Filter have been designed at a cut-off frequency of 159kHz employing equal resistance and capacitance values i.e., 1kΩ resistors and 1nF capacitors. Cutoff frequencies obtained in simulations were quite consistent with theoretical cutoff frequencies with errors in percentage terms being 1.10%, 0.44% and 1.38% for BPF, HPF and LPF respectively. Gain and Phase responses of filters derived from simulations were highly consistent with the theoretical MATLAB graphs for all the frequencies considered. The Monte Carlo simulation performed using a 10% tolerance for resistors and 5% tolerance for capacitors for 100 runs proved the stability and closeness to the desired cutoff frequency of all three filter responses. Histogram simulation also indicated that all three cutoff frequencies have Gaussian distributions with very small standard deviations. Therefore, the design appears to be highly robust and tolerant of variations in the values of components used. Thus, all simulations clearly verify the theoretical analysis in Chapter 3.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The proposed circuit in this thesis has shown that by using minimum passive components with CFOA different active filters can be obtained. This simple suggested circuit can be used for various applications in different domains. The theoretical analysis is validated by simulation results, which also verify that the circuits achieve the intended frequency selective characteristics.. This proposed current feedback operational amplifier based approach is very useful for wideband applications where conventional op amp based filters face gain-bandwidth limitations.

5.2 Future Work

- Higher-Order Filter Topologies: Cascading of several stages of CFOA to design fourth and sixth order filters with Butterworth, Chebyshev or Bessel roll-off characteristics.

- Electronically Tunable Filters: One key drawback of filter circuits with fixed components is that the filter parameters cannot be varied after the construction of the filter. Further studies should therefore examine the use of Voltage-Controlled Resistors (VCRs) to replace the fixed resistors used in the CFOA filters to make the design electronically tunable.

- Current-Mode Implementation: Utilizing the CMOS IC technology to make the filter chip small in size and suitable for large-scale manufacturing. Cascading several CFOAs in Higher Order Filter Topologies to get fourth and sixth order filter responses with Butterworth, Chebyshev or Bessel characteristics.

- Minimization of Sensitivity: The future research work on active filters should concentrate on developing ways to reduce the sensitivity of these filters to component variances through the use of computational methods.

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