Govt. of N.C.T. of Delhi

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Shahbad Daulatpur,Main Bawana Road, Delhi-42

Proforma for Submission of M.Tech. Major Project

01. Name of the Student..AYUSH GAUTAM.....

02. Enrolment No ..24/CAI/05..........

03. Year of Admission ......2024...............

04. Programme M.Tech., Branch....CAI........

05. Name of Department....EE............................

06. Admission Category i.e. Full Time/ Full Time (Sponsored)/ Part Time:.....F.T..............

07. Applied as Regular/ Ex-student..Regular..............

08. Span Period Expired on ....

09. Extension of Span Period Granted or Not Granted (if applicable)..............................

10. Title of Thesis/ Major Project.CFOA based mixed Mode Active ....
...Filter Configuraton...

11. Name of Supervisor....Dr. Garima..

12. Result Details (Enclose Copy of Mark sheets of all semesters) :

S. No.	Semester	Passing Year	Roll No.	Marks Obtained	Max. Marks	% of Marks	Details of Back Paper Cleared (if any)
01	1st	2024	24/CAI/05	7.92	10	79.2%	-
02	2nd	2025	24/CAI/05	8.50	10	85%	-
03	3rd	2025	24/CAI/05	8.00	10	80%	
04	4th (P/T only)						
05	5th (P/T only)						

13. Fee Details (Enclose the Fee Receipt):

Amount Paid (in Rs.)........3000/-............	Receipt No. DOPS610976...	Date 28/05/26

AGautam

Signature of Student

It is certified that the name of Examiners for evaluation of the above thesis/ project have already been recommended by the BOS.

Garima

Signature of Supervisor

Signature of HOD with Seal

(Instructions for filling up the Form may see on back side please.)

Professor & Head
Electrical Engineering Department
Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road, Delhi - 110042

DELHI TECHNOLOGICAL UNIVERSITY

Proforma for submission of thesis/dissertation

Student Name	Registration Number	Course and Branch	Title of the dissertation	Name of the Guide
AYUSH GAUTAM	24/C&I/05	MTech (C&I)	CFOA based mixed mode biquad active filter configurations	Dr. Garima

Above work has been carried out by me under the supervision of
Dr. Garima

and due care has been taken to acknowledge the work of authors referred in the presen thesis/dissertation. To the best of my knowledge the work is free from plagiarism as per the approved policy for plagiarism of Delhi Technology University. This may please be forwarded to the library for providing the similarity report from software.

Signature of studen

Above dissertation/thesis entitled containing 240 may please be checked by the softwar available in the library and the similarity report may be forwarded to the undersigned.

Supervisor's Signature
Email

Head Department
Email

Professor & Head
Electrical Engineering Department
Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road, Delhi - 110042

Plagiarism checking section (library)

The aforementioned thesis have been checked and 9% similarity is found. The detaile report is being forwarded to the above mentioned e-mail IDs for further reference at th end of the concerned Department

Signature
Seal of the Library
Sl. No. of Register 2258

10/6/26

S. No. 439334

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

STATEMENT OF GRADES

Master of Technology

(Control & Instrumentation)

Name : AYUSH GAUTAM
Roll No. : 24/C&I/05
Month & Year of Examination : NOV 2024
Semester : FIRST

Subject Code	Subject Title	Credits	Credits Secured	Grade
C&I501	SYSTEM THEORY	4	4	A
C&I505	NON LINEAR CONTROL THEORY	4	4	A+
C&I507	ANALOG AND DIGITAL ELECTRONICS	4	4	A
C&I509	SCADA AND EMS	4	4	B+
C&I523	PCB DESIGN	2	2	A+
C&I525	SELF-STUDY	2	2	A
C&I5313	SOFT COMPUTING TECHNIQUES	4	4	B+
UEC501	AUDIT COURSE	0	0	A+
		24	24	

AB : Absent   DT : Detained

Credits Secured / Total : 24 / 24

SGPA: 7.92

Dated : March 17, 2026
Date of Declaration of Result :
April 07, 2025

CONTROLLER OF EXAMINATION

S. No. 420682

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

STATEMENT OF GRADES

Master of Technology

(Control & Instrumentation)

Name : AYUSH GAUTAM

Month & Year of Examination : MAY 2025

Roll No. : 24/C&I/05

Semester : SECOND

Subject Code	Subject Title	Credits	Credits Secured	Grade
C&I502n	INTELLIGENT CONTROL	4	4	A
C&I504n	PROCESS CONTROL	4	4	A
C&I5321n	ADVANCED CONTROL SYSTEM DESIGN	4	4	A+
C&I5343n	ELECTRICAL ENERGY STORAGE SYSTEM	4	4	A+
C&I546n	SKILL ENHANCEMENT COURSE 2	4	4	A
UCC502n	RESEARCH METHODOLOGY	4	4	A+
		24	24	

AB : Absent DT : Detained

Credits Secured / Total : 24 / 24

SGPA : 8.50

Dated : September 10, 2025

Date of Declaration of Result : July 29, 2025

RPandey

CONTROLLER OF EXAMINATION

Delhi Technological University

(Formerly Delhi College of Engineering)

THE RESULT OF THE CANDIDATE WHO APPEARED IN THE FOLLOWING EXAMINATION HELD IN NOV 2025 IS DECLARED AS UNDER:-

Master of Technology(Control & Instrumentation), III-SEMESTER

Result Declaration Date : 16-Mar-2026 **Notification No: 1942**

C&I601n : Motion Control of Electrical Motors C&I603n : Minor Project/Research Thesis/Patent OEN601 : Green Technology & Sustainability

Sr.No	Roll No.	Name of Student	C&I601n	C&I603n	OEN601	SGPA	TC	Failed Courses
			4.00	8.00	4.00			
1	24/C&I/01	PRASHANT KUMAR	B+	A	B+	7.50	16	
2	24/C&I/04	MONISHA SINGH	A	A+	A	8.50	16	
3	24/C&I/05	AYUSH GAUTAM	O	A	B	8.00	16	
4	24/C&I/07	SUBHAM KUMAR AGRAWAL	B	A	B+	7.25	16	
5	24/C&I/08	DAKSH	B+	A	B+	7.50	16	
6	24/C&I/09	AYUSH DIMRI	A	A	A	8.00	16	
7	24/C&I/10	NAMAN KUMAR	O	A	A	8.50	16	
8	24/C&I/11	AYAN REHMAN	A+	A	B+	8.00	16	
9	24/C&I/12	DEVENDER KUMAR	B	B+	B+	6.75	16	
10	24/C&I/13	VINEET TOMAR	A	A+	B	8.00	16	
11	24/C&I/14	SARASWAT AKSHAYA PATI	B	A+	B	7.50	16	
12	24/C&I/15	PRATISTHA SHARMA	B+	O	A	8.75	16	
13	24/C&I/16	HEMANT	B	A	B	7.00	16	
14	24/C&I/17	VARDAAN SINGH THAKUR	B	B+	C	6.25	16	
15	24/C&I/18	PRAGATI SATTAVAN	B+	A+	B+	8.00	16	
16	24/C&I/19	ABHISHEK MISHRA	O	A+	B	8.50	16	
17	24/C&I/20	MEGHA ARYA	B	A	B+	7.25	16	
18	24/C&I/21	ASHUTOSH KUMAR MISHRA	C	A	B+	7.00	16	
19	24/C&I/22	DHRATIKA SINGH	A	A+	B+	8.25	16	
20	24/C&I/23	SAUMYA TIWARI	B+	O	C	8.00	16	

C&I603n : Minor Project/Research Thesis/Patent

OIC (Results) **Controller of Examination**

Note: Any discrepancy in the result in r/o name/roll no/registration/marks/grades/course code/title should be brought to the notice of Controller of Examination/OIC(Results) within 15 days of declaration of result, in the prescribed proforma.

e-Receipt for State Bank Collect Payment

REGISTRAR, DTU (RECEIPT A/C)

BAWANA ROAD, SHAHABAD DAULATPUR, , DELHI-110042
Date: 28-May-2026

SBCollect Reference Number :	DUP5610976	**Category :**	Miscellaneous Fees from students
Amount :	₹3000		
University Roll No :	24/C&I/05		
Name of the student :	AYUSH GAUTAM		
Academic Year :	2025-26		
Branch Course :	MTECH C&I		
Type/Name of fee :	Others if any		
Remarks if any :	MTECH THESIS FEE		
Mobile No. of the student :	7838089920		
Fee Amount :	3000		
Transaction charge :	0.00		
Total Amount (In Figures) :	3,000.00	**Total Amount (In words) :**	Rupees Three Thousand Only
Remarks :		**Notification 1:**	Late Registration Fee, Hostel Room rent for internship, Hostel cooler rent, Transcript fee (Within 5 years Rs.1500/- & $150 in USD, More than

		5 years but less than 10 years Rs.2500/- & $250 in USD, More than 10 years Rs.5000/- & $500 in USD) Additional copies Rs.200/- each & $20 in USD each, I-card fee,Character certificate Rs.500/-.
Notification 2:	Migration Certificate Rs.500/-, Bonafide certificate Rs.200/-, Special certificate (any other certificate not covered in above list) Rs.1000/-,Provisional certificate Rs.500/-, Duplicate Mark sheet (Within 5 years Rs.2500/- & $250 in USD, More than 5 years but less than 10 years Rs.4000/- & $400 in USD, More than 10 years Rs.10000/- & $1000 in USD)	

Thank you for choosing SB Collect. If you have any query / grievances regarding the transaction, please contact us

Toll-free helpline number i.e. 1800-1111-09 / 1800 - 1234/1800 2100

Email -: sbcollect@sbi.co.in

CFOA BASED MIXED MODE BIQUAD ACTIVE FILTERS CONFIGURATIONS

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
IN
CONTROL & INSTRUMENTATION

SUBMITTED BY:
AYUSH GAUTAM
(24/C&I/05)

Under the supervision of
DR. GARIMA

ELECTRICAL ENGINEERING DEPARTMENT

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

MAY 2026

CONTENTS

CANDIDATE'S DECLARATION

I, **Ayush Gautam**, Roll No. **24/C&I/05** of MTech (Control & Instrumentation), hereby declare that the project Dissertation titled "**CFOA-base mixed mode biquad active filter configurations**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi

Date: 10/06/26

AGautam.

(AYUSH GAUTAM)

CERTIFICATE

I hereby certify that the Project Dissertation titled " **CFOA-base mixed mode biquad active filter configurations**" which is submitted by **Ayush Gautam**, Roll No. **24/C&I/05** Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Garima

Place: Delhi

Date:

(DR. GARIMA)

ASSOCIATE PROFESSOR

ELECTRICAL DEPARTMENT

ACKNOWLEDGEMENT

I would like to express my sincere and heartfelt thanks to **Dr. Garima**, without her active guidance, help, cooperation and encouragement I would not have been able to present the report on time. I would also like to extend my profound gratitude towards all others who gave their contributions to the completion of my project report.

Ayush Gautam

24/C&I/05

ABSTRACT

A current feedback operational amplifier (CFOA) based mixed-mode active biquad filter configuration is illustrated in this work. The proposed topology provides second-order low-pass(LP), band-pass(BP), high-pass (HP) and band reject (BR) responses simultaneously at different output nodes. The topology's major feature is its ability to operate in voltage mode(VM), current mode(CM), transadmittance mode(TAM) and transimpedance mode(TIM) without requiring any circuit reconfiguration. The circuit is realized using CFOA-based summer followed by two CFOA-based integrators and CFOA based voltage to current converter, making the circuit suitable for integrated implementation. Different mixed mode transfer functions are derived using ideal CFOA characteristics. Theoretical analyses are validated through simulation results, performed in Pspice, confirming correct second order frequency responses using AD844 type IC CFOA.

Keywords: CFOA, mixed mode filter, biquad filter, voltage mode, current mode transadmittance, transimpedance.

LIST OF FIGURES

LIST OF ABBREVIATIONS

S. No.	Abbreviations	Descriptions
1	CFOA	Current Feedback Operational Amplifier
2	VOA	Voltage Operational Amplifier
3	VM	Voltage Mode
4	CM	Current Mode
5	TAM	Transadmittance Mode
6	TIM	Transimpedance Mode
7	HPF	High Pass Filter
8	LPF	Low Pass Filter
9	BPF	Band Pass Filter
10	BRF	Band Reject Filter

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Active Building Blocks for Analog Signal Processing

The rapid development of modern integrated circuit technology has greatly increased the need for high speed, low voltage and power Analog Signal Processing systems. Consequently researchers have focused more on current mode and mixed mode Signal Processing techniques. These advancements have resulted in various active building blocks tailored for analog applications like filters, oscillators, instrumentation circuits and communication systems.

One of the earliest and most important active components is the operational amplifier (Op-Amp) , which has served as a key analog building block for years. While op-amps offer high gain and good accuracy through negative feedback, their performance is limited in high frequency applications because of restricted slew rate and gain bandwidth product. To address these issues, current mode active elements were developed. For example current conveyor (CC), particularly the second generation current conveyor (CCII), which gained wide popularity.

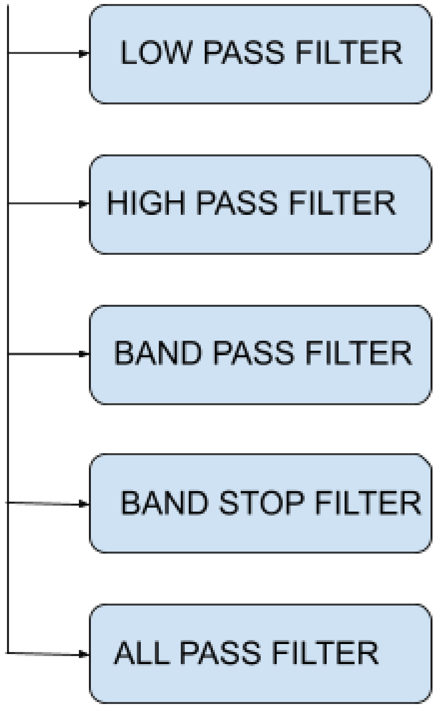
Ongoing research has produced several modified versions of current conveyor Including differential voltage current conveyors (DVCC), differential difference current conveyor (DDCC), current controlled current conveyors (CCCII) and fully differential current conveyors (FDCCII).

Another commonly used active building blocks the operational transconductance amplifier (OTA). To improve analog signal processing capabilities, engineers develop several hybrid active elements by combining features of existing devices. Examples include current differencing buffered amplifier (CDBA), current differencing transconductance amplifier (CDTA), current conveyor transconductance amplifier (CCTA) and current feedback operational amplifier (CFOA).

These combinations enhance circuit flexibility and decrease the number of passive components needed for implementation. The ongoing development of active building blocks is driven by the need for higher operating speed, low power use, better accuracy and simple circuits. Modern analog systems increasingly use these active elements because they offer flexible solutions for creating multifunctional and high performance circuits. Therefore studying and developing active building blocks continues to be a key area of research in analog signal processing and integrated circuit design.

1.2 Classification of Filters

Filters can be classified as :



The importance of active filters include providing high power gain and high speed performance.

1.2.1 Low pass filters:

They allow low frequency signals to pass while attenuating those that exceed the cutoff/pole/resonance frequency. The standard transfer function equation for biquad LPF can be written as

$$TF_{LP}(s) = \frac{K.\omega_o^2}{s^2+\frac{\omega_0}{Q}s+\omega_o^2} \qquad (1.1)$$

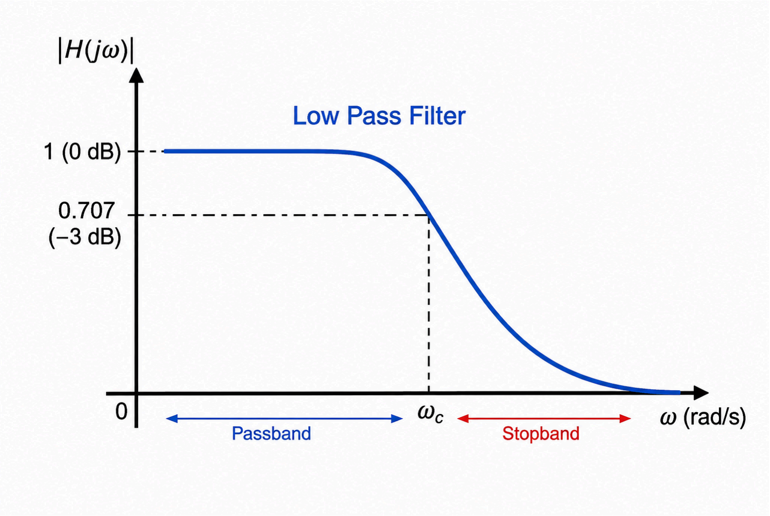


Fig. 1.1 Low Pass Filter Response Graph

1.2.2 High pass filters:

They allow high frequency signals above a certain cutoff/pole/resonance frequency while reducing the strength of lower frequencies. The standard transfer function equation for biquad HPF can be written as:

$$TF_{HP}(s) = \frac{K.s^2}{s^2+\frac{\omega_0}{Q}s+\omega_o^2} \qquad (1.2)$$

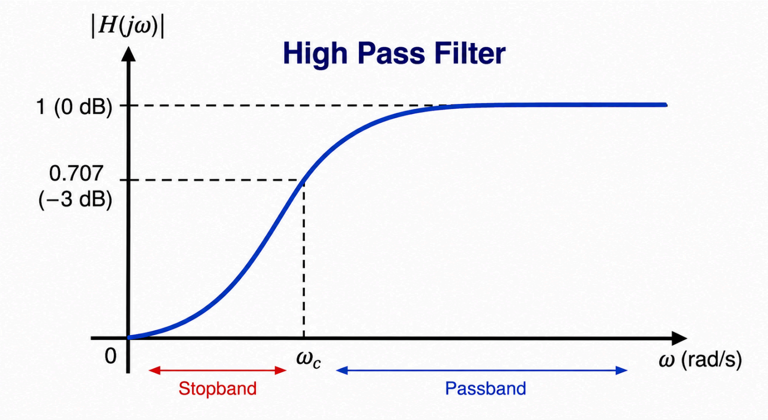


Fig. 1.2 High Pass Filter Response Graph

1.2.3 Band pass filters:

They allow signals with a specific to pass while filtering out those that are not in range. The standard transfer function equation for biquad BPF can be written as:

$$TF_{BP}(s) = \frac{K.\frac{\omega_o}{Q}.s}{s^2+\frac{\omega_0}{Q}s+\omega_o^2} \tag{1.3}$$

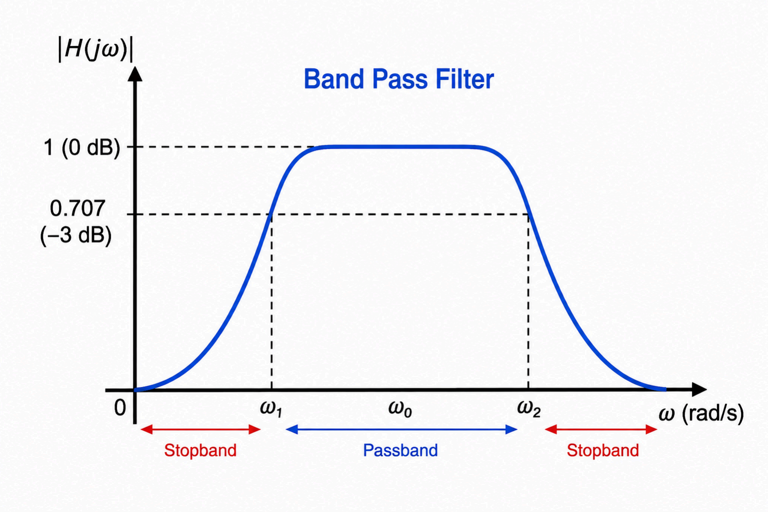


Fig. 1.3 Band Pass Filter Response Graph

1.2.4 Band stop filters:

Also called Notch filter, can block a band of frequencies while allowing other frequencies. They are further classified as wide and narrow band stop filters. The standard transfer function equation for biquad BRF can be written as:

$$TF_{BS}(s) = \frac{K(s^2+\omega_o^{\ 2})}{s^2+\frac{\omega_0}{Q}s+\omega_o^{\ 2}} \tag{1.4}$$

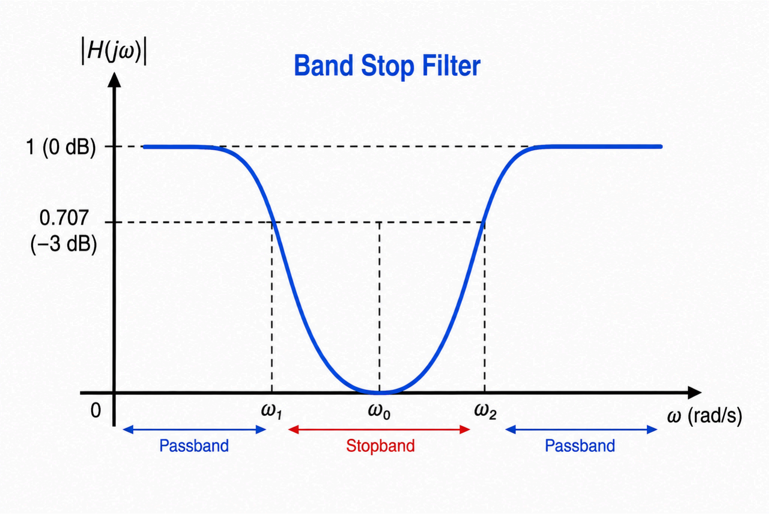


Fig. 1.4 Band Stop Filter Response Graph

1.2.5 All pass filters:

They permit all frequencies to pass through it. The standard transfer function equation for biquad APF can be written as:

$$TF_{AP}(s) = \frac{K(s^2-\frac{\omega_o}{Q}s+\omega_o^{\ 2})}{s^2+\frac{\omega_0}{Q}s+\omega_o^{\ 2}} \tag{1.5}$$

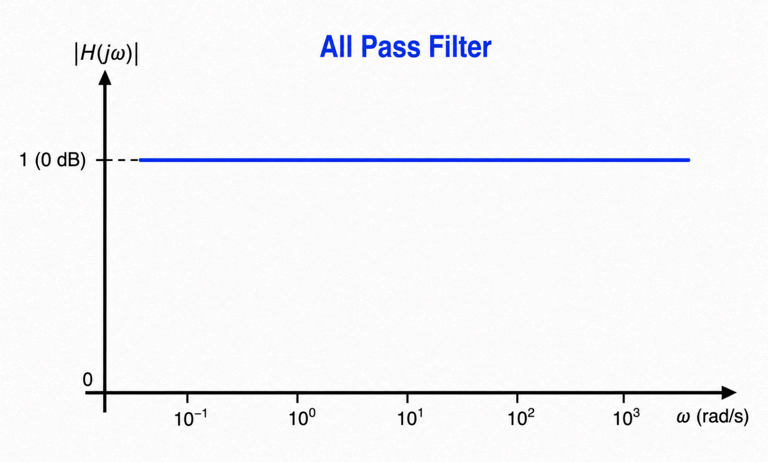


Fig. 1.5 All Pass Filter Response Graph

1.4 Introduction to this work

One of the most crucial components of modern electronics and communication systems is the analog filter. Signal conditioning, biomedical instrumentation, communication receivers, audio processing, control systems, oscillators, equalizers, radar systems and waveform shaping circuits are just a few of the many uses for them. Depending on the frequency range allowed to pass through the circuit, filters are generally classified as low pass, high pass, band pass, band reject and all pass filters. Because of its greater selectivity, frequency response control and ability to achieve higher order filtering functions through cascade techniques, second order or biquadratic filters hold a prominent position among these.

Traditionally, active filters were realized using voltage operational amplifiers (VOA). VOA- based filters have a number of drawbacks, including a limited slew rate, a limited gain bandwidth product and poor high frequency response, even though they provide acceptable performance at low and moderate frequencies. When wide bandwidth and improved dynamic performance are needed in today's high speed analogue system, these disadvantages become more noticeable. Current Feedback Operational Amplifiers (CFOA), a current mode active building block, have attracted considerable attention from researchers in order to circumvent these restrictions. CFOAs have high slew rate, broad bandwidth, excellent dynamic properties and low output impedance therefore they are ideal for high frequency analog signal processing.

It is structurally derived from the second generation current conveyor (CCII+), followed by a voltage buffer connected at the Z terminal.

Over the past few decades, significant research has focused on the development of CFOA-based multifunctional and universal filters. Researchers have focused on establishing mixed mode operation, reducing sensitivity, enhancing high frequency performance and tunability and reducing the number of components. The use of CFOAs has been made to report different types of universal filter structures that can provide low pass, band pass, high pass, band reject and all pass filter configurations. Grounded capacitors, which reduce parasitic effects and occupy less silicon area, are used in many of these circuits, making them ideal for IC fabrication.

Mixed mode filters' realization is another major trend in filter design of today's scenario. Mixed mode filters can concurrently perform voltage mode, current mode, transadmittance and transimpedance mode operations, in contrast to traditional single mode filters that only function in voltage mode.

This paper proposes a novel mixed mode biquadratic universal filter configuration based on CFOA. To achieve second order filtering operations, this suggested design makes use of a set of resistors, grounded capacitors and 5 CFOAs. Without changing the circuit architecture, the circuit can simultaneously provide high pass, low pass, band pass and band reject responses in voltage mode, current mode, transadmittance mode and transimpedance mode.

The filter is designed for butterworth response characteristics and validated through OrCAD Pspice using the AD844 library.

CHAPTER 2

LITERATURE REVIEW

2.1 First Order Filters

First order filters and second order filters are essential components of analog signal processing systems and are widely used in oscillators, control applications, biomedical electronics, communication systems, phase equalization and waveform shaping. Due to its wide bandwidth, high slew rate, low output impedance and better high frequency performance than traditional voltage operational amplifiers, the current feedback operational amplifiers (CFOA) has become one of the most appealing active building blocks for filter realization. Compact, low component count, mixed mode electronically adjustable filter designs using CFOAs have been the focus of significant research efforts in recent years.

The development of CFOA based first order universal filters in addition to offering low pass(LP), high pass(HP), all pass(AP) responses from a single topology, these filters have grown in significance because they are crucial building blocks for the realization of higher order filters, oscillators, phase shifters, equalizers and communication circuits. Researchers have mostly concentrated on enhancing aspects such as circuit simplicity, less active and passive components, grounded passive element utilisation, independent tunability, mixed mode operation and improved cascadability, according to a survey of recent literature.

Two Innovative CFOA based first order voltage mode universal filter designs that can achieve low pass, high pass and all pass responses with the fewest passive components were presented by Dogan et al. In order to ensure easy cascading capabilities, the suggested circuits use an additional unity gain inverting amplifier and provide both high input impedance and low output impedance characteristics. A single resistor and capacitor are used in one of the suggested filters, whereas grounded resistors and a capacitor are used in the second topology, which makes the design more appropriate for integrated circuit implementation. The authors noticed that many previous first order voltage mode filters either lacked universality, required many active devices, suffered from passive component matching restrictions or did not offer low output impedance characteristics.

Without requiring circuit alteration Dogan's initial suggested arrangement achieves low pass, high pass and all pass responses by carefully choosing input terminals. The transfer functions show that the pole frequency has low passive sensitivity and is dependent on the passive RC product. The derivation of the quadrature oscillator circuits from the suggested filter architectures is another significant contribution of this work. The impact of non ideal CFOA gains and parasitic impedance on the filter response were also examined. The theoretical approach was validated experimentally using commercially available AD844 ICs and through extensive Spice simulations. The study showed that the CFOA based first order filters can preserve desired impedance characteristics while achieving high frequency operation with less complexity.[1]

Two simple mixed mode first order universal filter designs using CFOAs were presented by Bhaskar et al. The suggested structures concurrently support voltage mode (VM), current mode(CM), transadmittance mode(TAM) and transimpedance mode(TIM) operations in contrast to traditional single mode filters. The second configuration achieves the identical responses in current and transimpedance mode whereas the first configuration produces low pass, high pass and all pass functions in voltage and transadmittance mode. This mixed mode capability increases circuits adaptability and usefulness to a great extent in modern analog signal processing system scenarios.

An important advantage is that grounded capacitors are simpler to design and take up less chip space area than floating capacitors. Most of the filter configurations require only one CFOA, three resistors and a grounded capacitor. Therefore, their use is particularly advantageous from a standard integrated circuit construction perspective.

The independent tunability of gain and pole frequency is another important feature of this work. Practical tunability was limited in many previous filter designs because changes in the pole frequency concurrently influenced the gain. However, by independently adjusting resistor values, the suggested combinations get around this restriction [2].

Additionally, a thorough comparison with previously published first order universal filters was conducted by the authors. It was demonstrated that many previous designs relied on non commercially accessible active devices, needed several active building blocks, lacked grounded capacitors or failed to provide appropriate input/output impedance levels for cascading. The suggested circuits, on the other hand, accomplished mixed mode functioning with less hardware complexity by using widely available AD844 type CFOAs. Further evidence of satisfactory match between theoretical and practical outcomes came from PSpice simulations and experimental verification. The development of small, multipurpose CFOA based Universal filters appropriate for contemporary integrated analog systems was greatly aided by this study [2].

Raj et al. extended the functionality of previously proposed CFOA based all pass filters to realize first order universal filters that can simultaneously provide low pass, high pass and all pass responses by expanding the capability of previously proposed CFOA based all pass filters. The increasing need for multifunctional active filters with grounded capacitors, low output impedance, high input impedance and tunable frequency characteristics drove the suggested work. Although a number of first order universal filters had previously been documented in the literature, the authors noted that only few configurations concurrently met all practical requirements, including gain controllability, commercial realizability, ease of cascading, and grounded passive elements [3].

The suggested configurations are generated through appropriate modifications of previous all-pass filter architectures and use of two CFOAs and a grounded capacitor. The thorough analysis and categorization of previous first order universal filters in both current mode and voltage mode is a significant contribution of this work. Based on factors such as operational mode, active element count, passive element count, grounded capacitor usage, tunability and impedance characteristics, the authors compared a variety of previously published designs. The comparison analysis demonstrated the benefits of the suggested designs and pointed out the shortcomings of the previous circuits [3].

Another important factor is the tunability of gain and pool frequency both at the same time of the suggested filters. Due to the high input impedance and low output impedance the suggested configurations are perfect for cascade realization. The usefulness of CFOA based universal filters for analog signal processing applications was validated through AD844 integrated circuit CFOA. The outputs of the experiments performed closely matched to that of theoretical results.

Nako in [4] proposed first order universal shadow filters using the active building block-CFOA, with scaled time dependent constants. Without changing the basic filter structure or without reconfiguration he established the idea of shadow filtering to scale the effective time constant, in contrast to traditional first order filters where the time constant depends directly on the RC product. This method is generally used where very high RC values are needed.

The application of CFOA compared to comparable operational amplifier or current conveyor realisations significantly decreased the amount of active and passive components needed. Furthermore, the suggested structures demonstrated low output impedance and high input impedance characteristics, guaranteeing superior cascadability for implementation of higher order filters. The efficiency of the suggested shadow filtering idea was confirmed by simulation and experimental findings. Additionally, the work illustrated a useful biomedical application that uses a field programmable analog array (FPAA) to create a high pass filter that removes base line drift from ECG signals. Through the integration of shadow filtering ideas with CFOA based architecture the study presented a novel approach to first order filter realisation[4].

The previously mentioned research makes clear that the main goals of current research trends in CFOA based first order filter design are multifunctionality, lower component counts, mixed mode operation, high frequency performance, tunability and enhanced impedance characteristics. Previous first order filters frequently had problems like high active device consumption, no grounded capacitors, few operating modes, low cascadability and no independent tuning capability. Through creative applications of CFOA and enhanced filter designs, the evaluated studies addressed many of these issues.

The growing focus on mixed mode and universal filter realisation is a recurring theme in the evaluated studies. With the ability to function in voltage, current, transadmittance and transimpedance modes, mixed mode filters offer more adaptability for connecting to a variety of analog systems. Additionally, the suggested circuits are economically feasible and empirically verifiable due to commercially available AD844 CFOAs. These circuits are better suited for monolithic integrated circuit implementation when grounded capacitors and grounded resistors are used.

From the previous literature, the use of first order filters as fundamental components for implementing higher order systems like quadrature oscillators, multi phase oscillators, equalizers and biquad filters is another significant conclusion. Several writers demonstrated the multifunctional applicability of these designs by directly driving oscillator structures from their suggested filter settings. For reliable practical operation, low sensitivity characteristics and parasitic impedance analysis are still crucial factors to take into account.

There are still several research gaps in the field of CFOA based active filter design, despite notable progress. Many documented first order universal filters do not concurrently provide all mixed mode functions and instead concentrate mostly on voltage mode operation. Certain configurations still include passive matching limits or need for several active devices. Additionally, while shadow filtering and tunability methods have been studied for the first order structures, their applications to the implementation of compact mixed mode biquad filters has received comparatively less attention. The development of CFOA based mixed mode biquad active filter designs with lower complexity, universal operation, electrical tunability, low sensitivity and integrated circuit compatibility is encouraged by these limits.

Therefore the current work on CFOA mixed mode biquad active filter designs has a solid foundation. The development of multifunctional mixed mode structures from basic first order universal filters illustrates the increasing significance of CFOA in contemporary analog signal processing applications. These studies' conclusions and limits offer important direction for creating better biquad filter topologies with better real world applications.

2.2 Second Order Filters

Due to their wide range of uses in communication systems, biomedical instrumentation, audio processing, oscillators, equalizers,, phase shifters, sensor interfaces and control systems, second order active filters and universal biquad structures are among the most significant classes of analog signal processing circuits. Thus , during the past thirty years there has been constant research interest in the development of small, low power, high frequency and multifunction active filters. The current feedback operational amplifier (CFOA) has become one of the most popular active building blocks because of its superior slew rate, wide bandwidth, high speed operation, low output impedance and practical implementation using commercially available AD844 integrated circuits.

In contrast to traditional voltage operational amplifiers, which have gain bandwidth constraints, CFOA are very appealing for the implementation of high frequency filters because they offer almost constant bandwidth irrespective of closed loop gain. As a result numerous CFOA based universal and multifunction filters reported in literature have an objective to improve tunability, support mixed mode operation, minimize sensitivity, increase cascadability and decrease component count.

One of the earlier contributions by Liu and Wu in this field suggested a novel CFOA based universal biquadratic filter that makes use of two current feedback amplifiers. All five common second order filter responses–low pass(LP), high pass(HP), band pass(BP), notch and all pass(AP) responses were accomplished by the suggested construction.

Compared to previous realizations, the circuit's hardware complexity was lower because it only used two CFOAs and six passive components.An additional key result from this research was the independent controllability of the natural frequency and the quality factor. Here, a grounded capacitor was utilized to individually vary the natural frequency and similarly an individual resistor can independently vary the quality factor. In addition, because of moderate sensitivity in both the active and passive components, the filter has been shown to have increased practical robustness with respect to variations in the values of its components. Experimentation confirmed that the theoretical studies on CFOA application to analog filters are valid [5].

Abuelma'atti and Al Zaher proposed utilizing two current feedback amplifiers in order to build another universal voltage mode second order filter. Using only five passive parts (three resistors and two capacitors), they were able to implement low pass, high pass, band pass, notch and all pass configurations. One of the major benefits was that it allowed orthogonal tuning of the quality factor and resonance frequency along with individual control of natural frequency and bandwidth. In addition, the circuit had a low output impedance allowing easy cascadability as well as realization of higher order filters. As stated by the authors, a number of prior circuits utilized either a larger number of elements or required changes to the passive component configuration to achieve multiple different filter responses. Conversely, the authors demonstrated how their proposed configuration can achieve all pass filter response types without requiring rearrangement of the passive element configuration or topology. Due to relatively low levels of both active and passive sensitivities, the authors felt that the proposed design would be quite practical.

Horng developed a large variety of multifunctional and universal CFOA-based filter configurations. The use of current feedback operational amplifiers was proposed by Horng in one of his contributions for creating a high input impedance voltage mode low pass, band pass and high pass filter. Four resistors (three grounded and one floating) and three grounded capacitors were used in the circuit to achieve low pass, high pass and band pass responses. The system maintained low active and passive sensitivities while offering orthogonal control over resonance frequency and quality factor. The topology was improved by the inclusion of grounded capacitors for integrated circuit implementation, also low output impedance of circuit features enhanced its cascadability[7].

With just one CFOA and a voltage follower Horng proposed a voltage mode multifunction filter in another work of his. With just two capacitors and two resistors, the filter was able to achieve low pass, high pass, band pass, notch and all pass responses from the same circuit layout. The circuit provided orthogonal tuning of natural frequency and bandwidth without imposing any component matching requirements. Reducing the number of active and passive components while maintaining universality and low sensitivity features was one of this topology’s main benefits. This work showed that CFOAs might be used to construct multifunction filters with low circuit complexity [8].

Horng also proposed a new universal voltage mode filter using current feedback amplifiers. All standard second order filter responses were realised by the configuration without the need for component matching requirements. Resonance frequency and bandwidth of the filter were orthogonally tuned and the circuit had characteristics of low sensitivity. Cascading was made possible because of the low output impedance without adding any extra buffer stages. The proposed circuit, when compared to previous universal biquad filters structures, was greatlty improved in compactness as it minimised the number of passive components with help of only 2 capacitors, two resistors and two CFOAs [9].

Later research efforts concentrated on enhancing the practical realisation elements of universal biquads, especially with regard to orthogonal tune ability and grounded capacitor implementation. A multiple input single output (MISO) universal biquad filter implemented with CFOAs was proposed by Nikoloudis and Psychalinos. A number of issues with previous MISO universal biquads were resolved by the proposed topology. Floating capacitors were necessary for many earlier designs, which reduced performance because of parasitic effects and difficult integrated implementation. Only grounded capacitors were used in the suggested circuit, which allowed for orthogonal modification of the resonant frequency and quality factor. Additionally, The design removed input signal value constraints that were present in previous topologies. The efficacy of the suggested design was verified experimentally using commercially available AD844 CFOA IC [10].

Bhaskar, Raj and Senani introduced three novel CFOA based SIMO type universal active filter configurations, which represent another significant breakthrough. From a single topology, second order universal active filters simultaneously realize low pass, high pass, band pass, band reject and all pass responses . Four CFOAs and two capacitors were used in the suggested circuit, which offered essentially infinite input impedance and zero output impedance.Application using voltage mode cascade greatly benefited from such impedance characteristics. Additionally, the suggested configuration included quality factor, gain and pole frequency to tunability.None of the previously published SIMO type CFOA based universal filters concurrently offered all these advantages with such a lower component count, the authors emphasized. The theoretical performance was confirmed by experimental results using AD844 ICs [11].

The second order multifunction filter integrated circuit based on CFOAs with independent voltage gain control was designed by Chen et al. This work concentrated on full integrated circuit realisation utilizing 0.18µm CMOS technology, in contrast to much earlier research that only employed simulations or discrete commercial IC implementations.The suggested voltage mode multifunction filter concurrently achieved low pass, inverted band pass and bandstop responses using two grounded capacitors and four resistors. The independent gain controllability of various filter responses was one of this work's main accomplishments. Additionally, the bandwidth and quality factor were adjusted orthogonally. With this study an important step towards practical monolithic integration of CFOA based multifunction filters was taken as the integrated circuit showed low power dissipation, good linearity and good phase noise performance.[12].

Chen, Wey, Wu, Wang and Chen made a more recent contribution in the literature in which they suggested a novel universal active filter with the help of commercially available AD844 CFOA ICs. Three CFOAs, two grounded capacitors and six resistors were used in the suggested voltage mode universal active filter. Low pass, high pass, band pass, band reject and all pass responses were simultaneously produced by the circuit using the same setup. The suggested filter produced all responses without the need for extra switching circuitry, in contrast to previous topologies that needed switches or voltage inverters for all pass realization. Direct cascading was made possible by the topology's high input impedance and low output impedance features. The design's implementation as a CFOA based device, which offered greater integration and reduced power consumption in comparison to discrete AD844 implementations, was another crucial component [13].

CFOA based fully orthogonal universal and multifunction filters in voltage mode and current mode topologies were presented by Dogan et al. The authors suggested a current mode SIMO multifunction filter with two CFOAs and voltage follower. The proposed structure provided minimum sensitivities, no passive elements matching requirements and orthogonal control of resonance frequency and quality factor. With low output impedance the voltage mode filter achieved low pass, high pass, band pass, band reject and all pass responses. By slightly altering the voltage mode structure, the current mode multifunction filter was obtained. The suggested circuits' practical applicability was validated by experimental testing utilizing AD844 ICs [14].

Inverse active filters using CFOA were investigated by Gupta et al. Regarding the correction of signal distortions in control and communication systems. Commercially available AD844 CFOAs were used to implement the suggested inverse low pass, inverse band pass, inverse high pass and inverse band reject filters. The work demonstrated how CFOAs may be used to realize both typical filter structures and specific inverse transfer functions needed for sophisticated analog signal processing applications [15].

Tangsrirat and Surakampontorn proposed a universal biquad filter and single resistance controlled quadrature oscillator using a minimum amount of passive components and just two CFOAs. Without the need for component matching limitations, the suggested universal biquad filter achieved all common second order filtering responses such as low pass, high pass, band pass band reject and all pass features. The orthogonal control of natural frequency and bandwidth was a major benefit of the proposed circuit. The circuit is appropriate for integrated implementations and cascading operations, according to the authors, because of grounded capacitors and low output impedance nodes. Results from experiments and Pspice simulations using AD844 CFOA IC were validated [16].

Using single specific CFOA(SCFOA) Erkan Yuce developed a completely integrable mixed mode universal biquad filter. Depending on the input option, the circuit might function in both current mode and voltage mode. While all pass and high pass responses were acquired by appropriate current interconnections. Low pass, band pass and notch responses were simultaneously provided by the suggested current mode filter. All universal filter functions could be produced by the virtual machine in realization. The independent management of resonance frequency and quality factor was one of the key characteristics of the suggested topology. Additionally, the use of grounded passive elements decreased parasitic effects and improved IC compatibility. The study showed that the circuit flexibility in analog signal processing systems is greatly increased by mixed mode operation [17].

Because of CFOAs applications in phase shifters, equalizers, oscillators, communication systems and all pass filter realizations it has also received a lot of attention. Senani, P Kumar and Bhaskar proposed several first order all pass filter designs using just two CFOAs and grounded capacitors. The circuit’s performance was confirmed by hardware implementation, Spice simulations and non-ideal analysis. The study emphasized that all pass filters are essential building blocks for synthesis of higher order active filters and their realization of quadrature and multiphase oscillators. The proposed circuit used fewer passive components and provided ideally infinite input impedance when compared to previous structures in the literature [18].

Mixed mode and multifunction universal filters that can simultaneously realize VM, CM, TAM and TIM responses have been a major focus of recent studies. Dogan, Yuce and Minaei made a significant contribution in this regard by proposing a second order current mode universal filter that can produce all pass, low pass, high pass, bandpass and notch responses. While avoiding passive component matching criteria for the majority of filtering operations, their circuits made use of grounded capacitors and few components. The LP and HP outputs were subtracted to generate the notch response, and the BP output was subtracted from notch response to create all pass response. In multifunction filter design, this technique of deriving all pass and notch characteristics from fundamental filter outputs has gained popularity [19].

In addition to addressing high frequency compensation methods to account for parasitic impedances related to CFOAs AK Singh and Senani suggested a CFOA based state variable biquad.When compared to previously published CFOA based biquads, the circuit showed better performance. Because they simultaneously produce LP, BP and HP outputs with low sensitivity characteristics, state variable filters are particularly significant. The authors used spice simulation based on macro models to confirm the feasibility of the suggested circuit [20].

VK Singh, AK Singh, Bhaskar and Senani proposed revolutionary mixed mode universal biquad that can simultaneously realise all five typical filtering responses in VM, CM, TAM and TIM modes, marking a significant advancement in CFOA based mixed mode filter design. Their topology was appropriate for integrated implementation because it used two grounded capacitors and four CFOAs. The study highlighted that the suggested setup provided full mixed mode capabilities when compared to previous CFOA based filters which typically only allowed 1 or 2 operational modes. The practical viability of the circuit was validated through experimental verification with AD844 CFOA library [21].

Wang et al. made another significant addition by proposing a high input impedance voltage mode multifunction biquadratic filter that uses two grounded capacitors, three resistors and three CFOAs. The circuit produced non inverting LP, BP and BR outputs at the same time. With the right excitation, HP and inverting BP outputs could also be obtained. The filter’s high input ingredients characteristic made it very helpful for cascading applications and it provided orthogonal control of resonance frequency and quality factor. A voltage mode quadrature oscillator with independently controlled oscillation frequency and condition was also realized using the same design [22].

In addition to filter realization, CFOAs have also been widely used in circuits for impedance and inductance simulators. Using CFOA Meghna et al. proposed floating parallel lossy inductance and capacitance simulators. These simulators were used in compensator circuits and higher order butterworth filter designs. The work demonstrated how CFOA based synthetic immittance circuits can achieve electronically adjustable passive counterparts without the need for physical inductors, increasing integrability and decreasing circuit space [23].

Tammam et al. examined the internal structure, dynamic responsiveness, bandwidth behaviour and common mode rejection properties of CFOAs in their critical theoretical analysis of CFOA topologies. The study examined how improved high frequency performance is a result of CFOAs' current mode functioning and low input impedance at X terminal. In order to further enhance bandwidth performance and reduce the impact of early effect, the study also suggested architectural modification utilising bootstrapping techniques [24].

Using CFOAs with grounded capacitors and orthogonal tuning capability, Nikoloudis and Psychalinos developed a multiple input single output universal biquad. Their suggested filter removed restrictions on input signal values while concurrently providing LP, HP, BP band stop and all pass responses. The authors emphasized the great utility of universal biquads in real world analog signal processing systems including touch tone telephone circuits, phase locked loops and communication systems [25].

A second order mixed mode multi input single output universal filter with three CFOAs, grounded capacitors and a few resistors was recently proposed by Alpasan [26]. The circuit produced all five common filter responses and enabled VM, CM, TAM and TIM operations. In addition to reviewing previously published second order universal filters in terms of operating mode, component count, grounded elements and implementation complexity the research pointed out the significance of mixed mode operation in modern day analog systems.

Soliman and Madian emphasized thorough analysis of MOS-C Kerwin Huelsman Newcomb (KHN) filter realizations employing CFOA [27]. It was beneficial in high frequency applications. Mixed mode universal filter configurations also saw significant improvements. Using a particular CFOA structure, Yuce proposed a fully integrable mixed mode universal biquad that can operate in both current and voltage mode with orthogonal control of resonance frequency and quality factor [28]. Liu presented a universal filter that uses two current feedback amplifiers to achieve typical biquadratic filtering responses with less circuit complexity [29].

The development of a universal voltage mode/ current mode biquad filter utilizing CFOAs by Senani and Gupta later made a substantial contribution to mixed operating mode filtering architectures [30]. A two CFOA based multifunction circuit with fewer passive components and improved multifunction capacity was recently proposed by Senani [31]. He also proposed a number of innovative CFOA based topologies with an emphasis on high frequency operation and fewer components for analog signal processing and signal generating applications in [32].

In the early 2000s, research on CFOA based multifunction and universal biquad filters received a lot of attention. NA Shah presented a flexible voltage mode CFOA based universal filter that can accomplish several filtering tasks without needing a lot of passive components. In order to improve cascade compatibility and practical implementation flexibility in [33]. He later presented a high input impedance voltage mode low pass, band pass and high pass filter employing current feedback amplifiers [34]. Furthermore, he expanded CFOA applications in [35] into hybrid active element filter architectures by creating voltage/current mode universal filters employing FTFN and CFOA. By creating voltage mode, current mode, transadmittance mode and transimpedance mode universal biquad filters utilizing plus type current feedback amplifiers, NA Shah considerably increased the operational capability of CFOA filters [36].

In order to increase integrability and reduce sensitivity issues, Sharma and Senani designed multifunction current mode and voltage mode biquads using single CFOA with grounded capacitors [37]. In a different contribution Sharma and Senani created universal current mode biquads with just one CFOA reducing the amount of active components used while preserving multifunctionality [38].

A new universal biquad using CFOA was proposed by VK Singh and Senani [39] with grounded capacitors and low sensitivity characteristics; it can implement conventional second order filtering operations. A significant improvement in multifunction CFOA filter design was later made when VK Singh et al. proposed a unique mixed mode universal biquad structure that could simultaneously realise voltage mode, current mode, transadmittance and transimpedance mode responses [40].

Additionally, Soliman thoroughly examined how current feedback operational amplifiers are used in analog integrated circuits, highlighting its applicability for high speed analog filter and oscillator realizations [41]. Using current feedback amplifiers, Topaloglu et al. introduced three input single output second order filters that allow for the flexible realization of various filter responses through input selection [42].

SF Wang et al. [43] subsequently presented a voltage mode multifunction biquadratic filter and quadrature oscillator employing grounded capacitance and CFOAs with orthogonal tuning capability. A high input impedance voltage mode multifunction filter that may concurrently provide many filtering responses appropriate for cascade applications was proposed by SF Wang in [44]. Wu et al. previously demonstrated the adaptability of current feedback amplifiers in achieving multifunction filtering operations by proposing a CFOA based universal filter developed from mason graph synthesis [45].

Table 1.1 Comparative features of the second order universal filter configurations

Reference	Name & Number of Actice Building Blocks	Grounded Capacitors Used	Number of Resistors	Operational Modes	Filters Realized
[46]	5 OTA	YES	0	VM, CM, TRM, TCM	AP, BP, LP, HP, BR
[47]	2-3 OTA	YES	3	VM	AP, BP, LP, HP
[48]	1 VDCC	YES	1	VM	AP, BP, LP, HP, BR
[49]	3 VCII	YES	6	VM	AP, BP, LP, HP, BR
[50]	1 DDCC	YES	0	CM	AP, BP, LP, HP, BR
[11]	4 CFOA	YES	6	VM	AP, BP, LP, HP, BR
[51]	1 VDDDA	YES	1	VM	BP
[52]	1 VDDDA	YES	2	VM	BP, LP, HP
[53]	2 VCII	YES	4	VM, CM	AP, BP, LP, HP
[54]	2 M-CCCCTA	YES	0	VM	AP, BP, LP, HP
[55]	2 CCII	YES	2	CM	BR, BP, LP, HP
[56]	2 CCII	YES	2	CM	BP
[57]	3 OTRA	NO	6	VM	LP, BP, HP

[58]	5 OTA	YES	0	VM	AP, BP, LP, HP, BR
[59]	2-MCCCCTA	YES	0	TCM	AP, BP, LP, HP, BR
[60]	3 CFOA	YES	4	VM	AP, BP, LP, HP
[61]	DXCCTA	YES	0	CM	BP, LP, HP
[62]	2 OTA	NO	0	VM	BP, LP, HP
[63]	2 VD-DIBA	YES	2	VM	AP, BP, LP, HP, BR
[64]	1 VDCC	YES	2	VM, CM	AP, BP, LP, HP, BR
[65]	2 VD-DIBA	YES	0	VM	AP, BP, LP, HP, BR
[66]	4 OTA	YES	0	VM	AP, BP, LP, HP, BR
[67]	1 CFTA	YES	0	CM	AP, BP, LP, HP, BR
[68]	1 DVCCTA	YES	3	CM, TIM	AP, BP, LP, HP, BR
[69]	2 VDBA	YES	0	VM	AP, BP, LP, HP, BR
This work	5 CFOA	YES	11	VM, CM, TAM,TIM	LP, HP, BP, BR

The literature research demonstrates how CFOA based first order and second order filter designs have evolved over the time. The research reveals the number of common benefits of CFOA based filter structures. Collectively, contributions demonstrate that CFOA based filters offer substantial advantages over traditional voltage operational amplifiers. These advantages include low output impedance, reduced component usage, orthogonal tuning, grounded capacitor implementation, low sensitivity, wider bandwidth, higher slew rate which makes them suitable for high frequency performance and support for VM, CM, TAM and TIM operations, all of which make them ideal for contemporary analog signal processing applications.

There are still certain research gaps and limitations despite significant progress. Multiple active devices are needed for many reported universal biquad structures, which increases silicon area and power consumption. Some topologies still include passive element matching limitations or floating capacitors, which make practical implementation more difficult.

For biquad structures, mixed mode operations that support VM, CM, TAM and TIM concurrently still comparatively remain less explored. Therefore there is a lot of room to design better mixed mode biquad active filter configurations by using CFOA.

CHAPTER 3

THE PROPOSED BIQUAD UNIVERSAL FILTER TOPOLOGY

3.1 Basic Concept of CFOA

As seen in Figure 1, the Current Feedback Operational Amplifier (CFOA) is a four port active component that has two input ports (X and Y) and two output ports (Z and W).

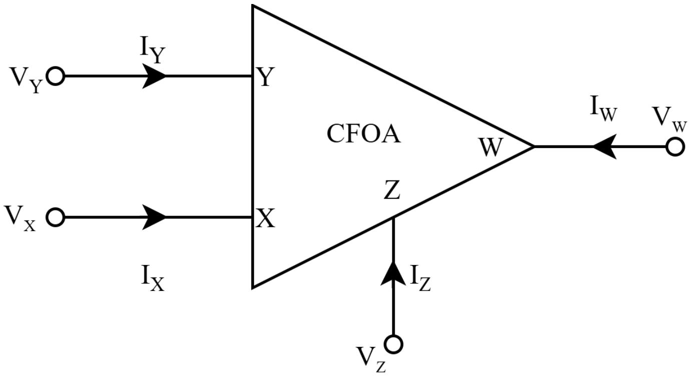


Fig. 3.1 Symbolic Representation of CFOA

It is structurally derived from the second generation current conveyor (CCII+) which is followed by a voltage buffer stage connected at the Z terminal. Its characteristics can be presented as following matrix equation:

$$\begin{bmatrix} I_Y \\ I_Z \\ V_X \\ V_W \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \eta \end{bmatrix} \begin{bmatrix} I_X \\ V_Y \\ V_Z \end{bmatrix} \tag{3.1}$$

α, β and η are frequency dependent non- ideal gains in the above equation. Under ideal conditions, all are equal to one. Thus, assuming ideal analysis of CFOA the terminal relations are defined as:

$$I_Y=0,\ V_X=V_Y,\ I_Z=I_X,\ V_W=V_Z \tag{3.2}$$

3.2 CFOA Integrator

The core of proposed topology utilizes a single CFOA based inverting integrator, shown in figure 2, where the integrating capacitor is connected at the high impedance Z terminal of the CFOA and the input signal is applied to low impedance X terminal via a resistor. The current entering the X terminal is transferred to the Z terminal in this configuration, with Y terminal grounded [70]. Its transfer function is given by:

$$\frac{V_o}{V_{in}} =- \frac{1}{sR_iC_f} \tag{3.3}$$

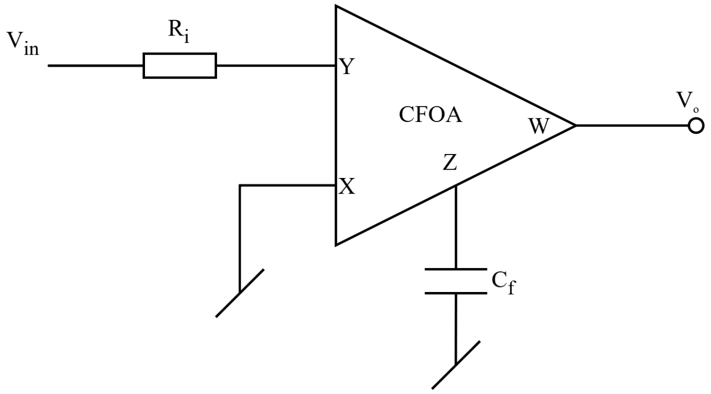


Fig 3.2. CFOA Based Inverting Integrator

3.3 The Proposed Configuration

Five CFOAs, eleven resistors including feedback resistors and two grounded capacitors are used in the proposed structure to create a second order mixed mode filter. The circuit is primarily composed of two cascaded CFOA based integrator stages after a summing amplifier stage. The input signal V_{in} is applied through resistor R_{in} in CFOA 1, which serves as input summing block. Feedback signals from the following stages are supplied back through R_f,R_{fb1} and R_{fb2}. Grounded capacitors C_1 and C_2 are used to create integrator stages from the outputs of CFOA 2 and 3. High pass, band pass and low pass responses are produced by the outputs V_{O1}, V_{O2} and V_{O3} respectively. Furthermore, CM and TAM filter responses can be realized because of CFOA 4 and 5 which are voltage to current converters. VM, CM, TAM and TIM filtering operations can all be realized simultaneously in the suggested circuit.

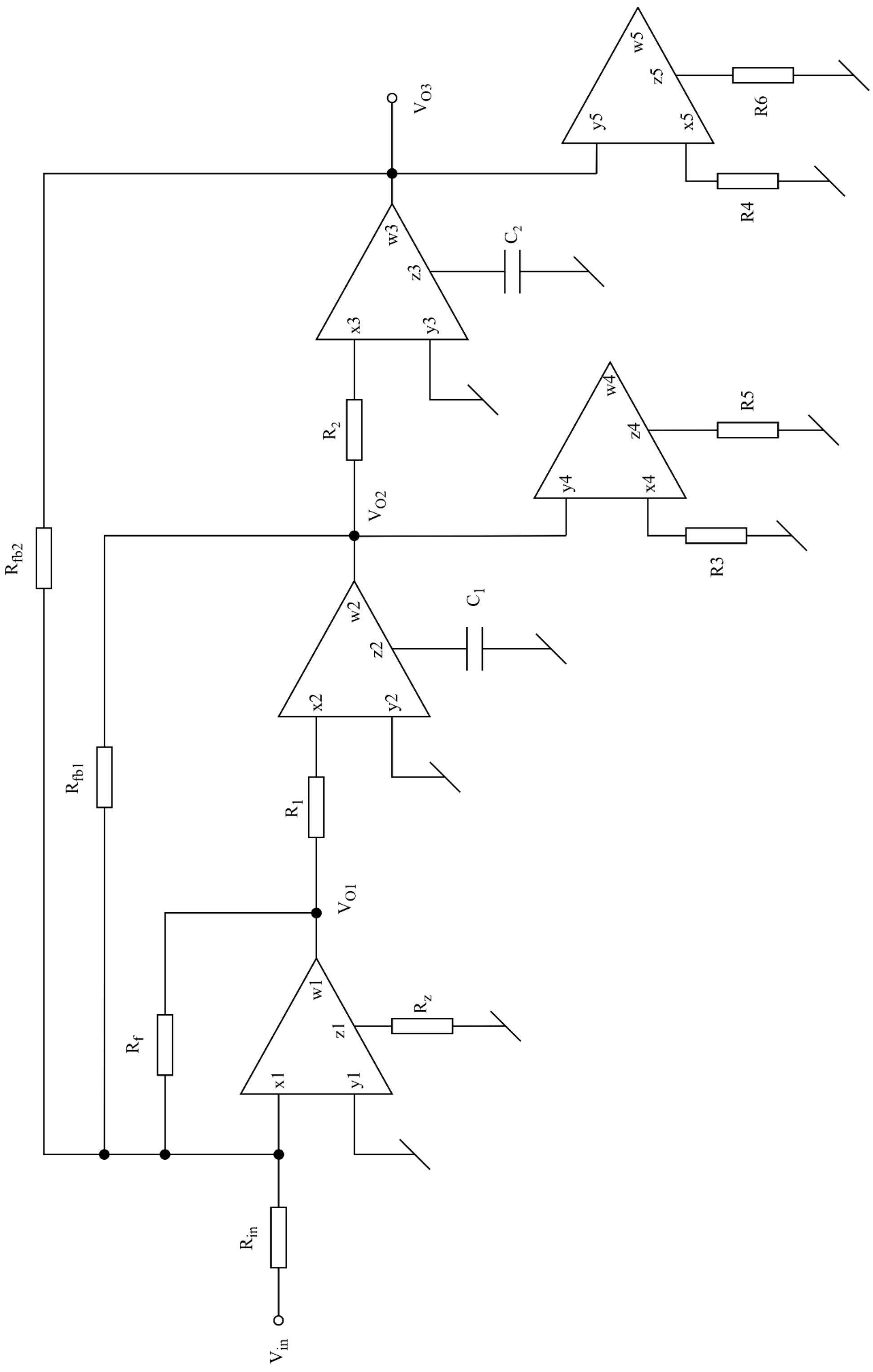


Fig 3.3. Proposed Circuit

3.4 Mixed-mode Transfer Functions

$$D(s) = s^2\left(\frac{R_z}{R_f} - 1\right) + s\frac{R_z}{R_{fb1}\tau_1} + \frac{R_z}{R_{fb2}\tau_1\tau_2} \tag{3.4}$$

where, $\tau_1 = R_1C_1$ (3.5)

and $\tau_2 = R_2C_2$ (3.6)

3.4.1 VM Transfer Functions

1. HPF:

$$\frac{V_{O1}(s)}{V_{in}(s)} = \left(-\frac{R_z}{R_{in}}\right)\frac{s^2}{D(s)} \tag{3.7}$$

2. BPF:

$$\frac{V_{02}(s)}{V_{in}(s)} = \left(-\frac{R_z}{R_{in}\tau_1}\right)\frac{s}{D(s)} \tag{3.8}$$

3. LPF:

$$\frac{V_{03}(s)}{V_{in}(s)} = \left(-\frac{R_z}{R_{in}\tau_1\tau_2}\right)\frac{1}{D(s)} \tag{3.9}$$

4. BRF:

$$H_{BRF}(s) = -\left(\frac{R_z}{R_{in}}\right)\frac{s^2+\frac{1}{\tau_1\tau_2}}{D(s)} \qquad (3.10)$$

3.4.2 CM Transfer Functions

1. HPF

$$\frac{I_{O1}(s)}{I_{in}(s)} = -\frac{s^2}{D(s)} \qquad (3.11)$$

2. BPF

$$\frac{I_{o4}(s)}{I_{in}(s)} = \left(-\frac{R_z}{R_3\tau_1}\right)\frac{s}{D(s)} \qquad (3.12)$$

3. LPF

$$\frac{I_{o5}(s)}{I_{in}(s)} = \left(-\frac{R_z}{R_4\tau_1\tau_2}\right)\frac{1}{D(s)} \qquad (3.13)$$

3.4.3 TAM Responses

1. HPF

$$\frac{I_{01}(s)}{V_{in}(s)} = -\left(\frac{1}{R_{in}}\right)\frac{s^{2}}{D(s)} \tag{3.14}$$

2. BPF

$$\frac{I_{04}(s)}{V_{in}(s)} = \left(-\frac{R_z}{R_{in}R_3\tau_1}\right)\frac{s}{D(s)} \tag{3.15}$$

3. LPF

$$\frac{I_{05}(s)}{V_{in}(s)} = \left(-\frac{R_z}{R_{in}R_4\tau_1\tau_2}\right)\frac{1}{D(s)} \tag{3.16}$$

3.4.4 TIM Transfer Functions

1. HPF

$$\frac{V_{O1}(s)}{I_{in}(s)} = -R_z \frac{s^2}{D(s)} \tag{3.17}$$

2. BPF

$$\frac{V_{O2}(s)}{I_{in}(s)} = \left(-\frac{R_z}{\tau_1}\right)\frac{s}{D(s)} \tag{3.18}$$

3. LPF

$$\frac{V_{O3}(s)}{I_{in}(s)} = \left(-\frac{R_z}{\tau_1\tau_2}\right)\frac{1}{D(s)} \tag{3.19}$$

4. BRF

$$H_{BRF}(s) = -\left(s^2 + \frac{1}{\tau_1\tau_2}\right)\frac{R_z}{D(s)} \tag{3.20}$$

From the above equations the filter parameters, resonance frequency (f_o) and quality factor (Q), can be given by:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{R_z}{R_{fb2}\tau_1\tau_2\left(\frac{R_z}{R_f}-1\right)}} \quad (3.21)$$

$$\text{and } Q = R_{fb1}\sqrt{\frac{\tau_1\left(\frac{R_z}{R_f}-1\right)}{R_z R_{fb2}\tau_2}} \quad (3.22)$$

Moreover, bandwidth can be expressed as:

$$BW = \frac{R_z}{R_{fb2}\tau_1\tau_2\left(\frac{R_z}{R_f}-1\right)} \quad (3.23)$$

CHAPTER 4

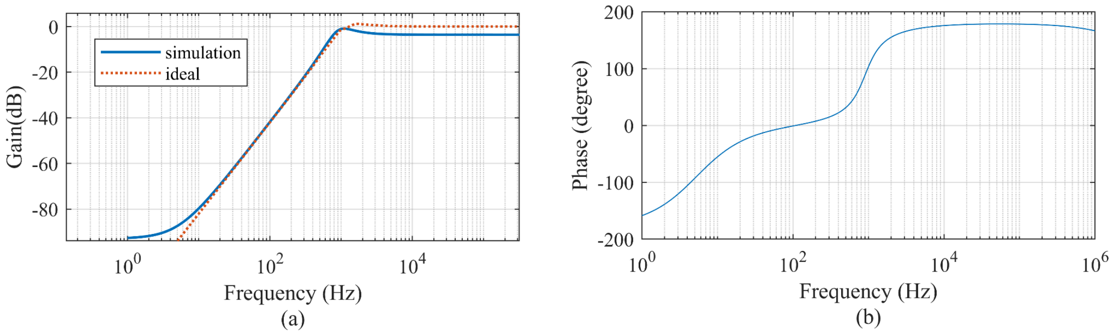
SIMULATION RESULTS

The performance of the proposed mixed mode CFOA based KHN biquad filter was verified using OrCAD PSpice simulation through the macro-model of AD844. For biasing of AD844, DC power supply voltages of symmetrical value ±12V were used. A sinusoidal AC voltage source with a magnitude of 1V was given as a supply to the filter input. An AC analysis was performed over a frequency range of 1Hz to 1MHz. The circuit was designed for a butterworth response that is Q=0.707 and for a resonant frequency of 1.59kHz. Therefore, the passive components were taken as $R_{in} = R_1 = R_2 = R_f =$ 10kΩ, R_z =20kΩ, R_{fb1}=14.14kΩ, R_{fb2}=20kΩ, $R_3 = R_4$ =10kHz, $R_5 = R_6$=20kHz and $C_1 = C_2$ =10nF. Frequency responses (magnitude and phase responses) for VM, CM, TAM and TIM have been demonstrated for different filter functions below:

4.1 Voltage Mode

4.1.1 High Pass Filter

For selected values of passive components: f_o=1.59KHz , Q=0.707



(a)

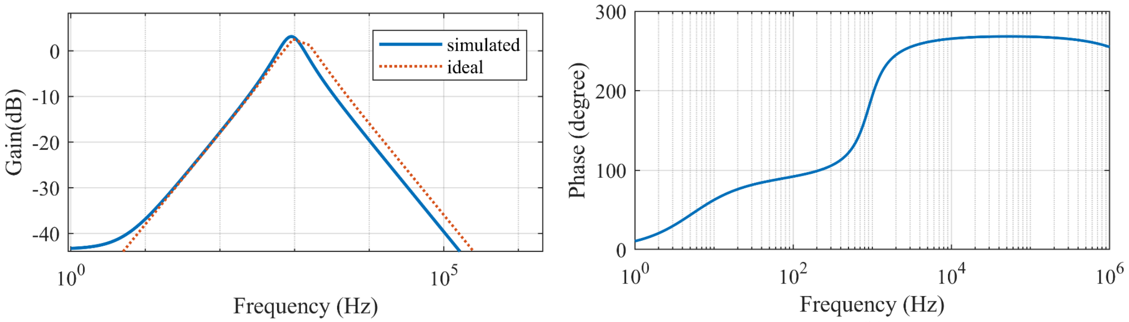
(b)

Fig. 4.1 a) Gain Response for f_o=1.59KHz b)Phase Response of HPF

From fig 4.1 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error less than 10% that might be because of the non-idealities of the CFOA.

4.1.2 Band Pass Filter

For selected values of passive components: f_o=1.59KHz , Q=0.707



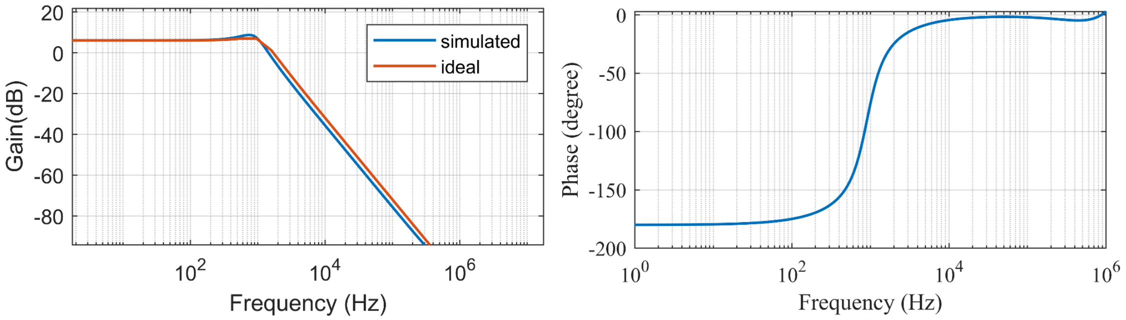
(a) (b)

Fig. 4.2 a) Gain Response for f_o=1.59KHz b)Phase Response of BPF

From fig 4.2 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 5% that might be because of the non-idealities of the CFOA.

4.1.3 Low Pass Filter

For selected values of passive components: f_o=1.59KHz , Q=0.707



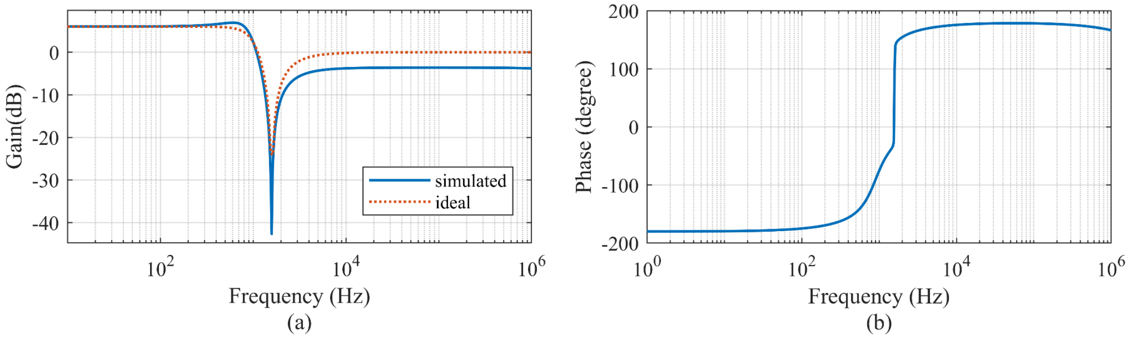
(a) (b)

Fig. 4.3 a) Gain Response for f_o=1.59KHz b)Phase Response of LPF

From fig 4.3 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 4% that might be because of the non-idealities of the CFOA.

4.1.4 Band Reject Filter

For selected values of passive components: f_o=1.59KHz , Q=0.707



(a)

(b)

Fig. 4.4 a) Gain Response for f_o=1.59KHz b)Phase Response of BSF

From fig 4.4 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 3% that might be because of the non-idealities of the CFOA.

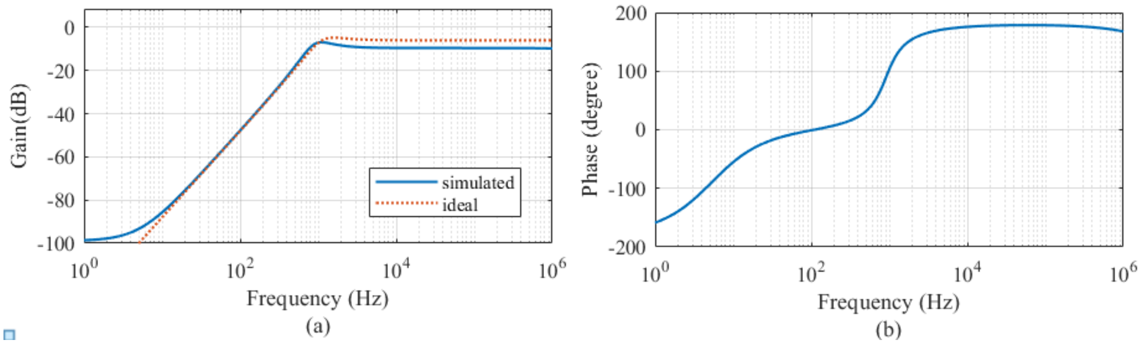
Table 4.1 Comparison table between simulated and theoretical values of Voltage Mode

Filter Type	Designed Frequency(kHz)	Simulated Frequency(kHz)	%Error
HPF	1.59	1.436	9.7
BPF	1.59	1.516	4.67
LPF	1.59	1.537	3.32
BSF	1.59	1.553	2.34

4.2. Current Mode

4.2.1 High Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707



(a)

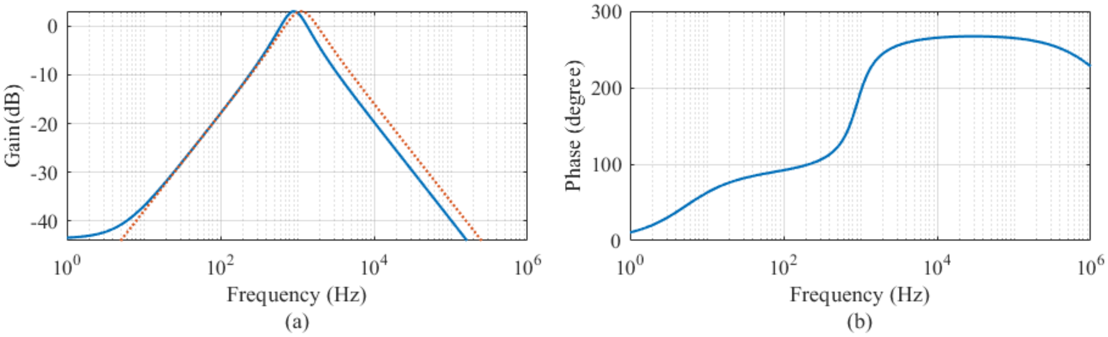
(b)

Fig. 4.5 a) Gain Response for f_o=1.59KHz b)Phase Response of HPF

From fig 4.5 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 10% that might be because of the non-idealities of the CFOA.

4.2.2 Band Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707



(a)

(b)

Fig. 4.6 a) Gain Response for f_o=1.59KHz b)Phase Response of BPF

From fig 4.6 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 6% that might be because of the non-idealities of the CFOA.

4.2.3 Low Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707

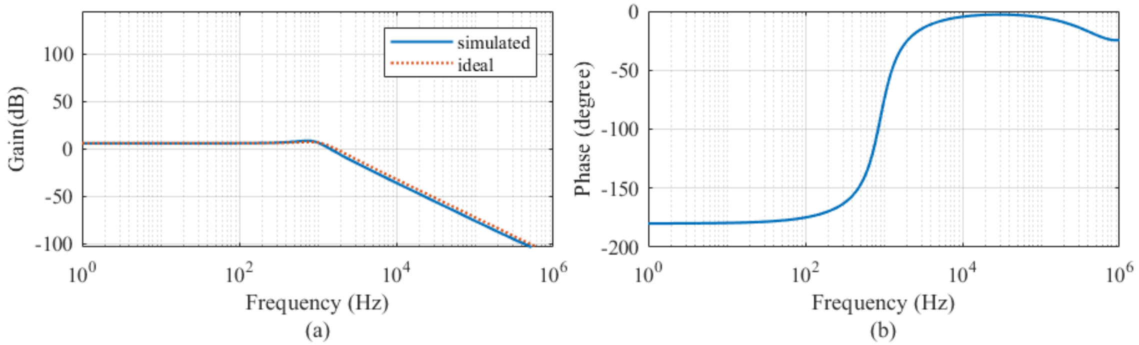


Fig. 4.7 a) Gain Response for f_o=1.59KHz c b)Phase Response of LPF

From fig 4.7 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 6% that might be because of the non-idealities of the CFOA.

Table 4.2 Comparison table between simulated and theoretical values of Current Mode

Filter Type	Designed Frequency(kHz)	Simulated Frequency(kHz)	%Error
HPF	1.59	1.451	8.76
BPF	1.59	1.509	5.12
LPF	1.59	1.510	5.04

4.3. Transadmittance Mode

4.3.1 High Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707

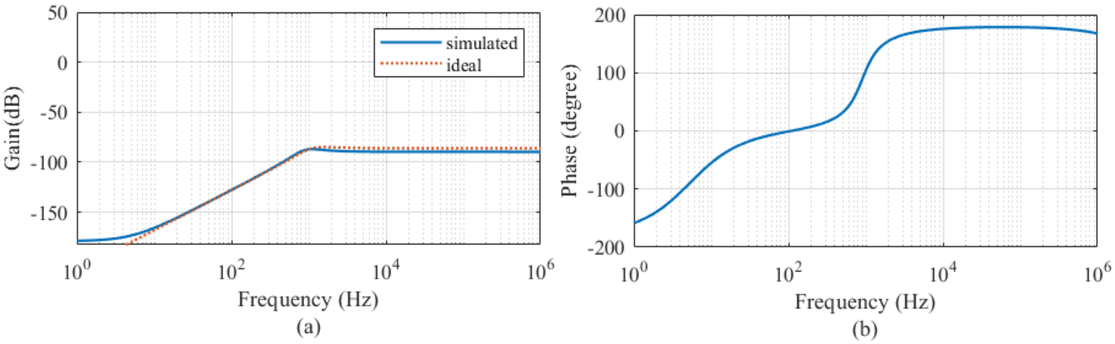


Fig. 4.8 a) Gain Response for f_o=1.59KHz b)Phase Response of HPF

From fig 4.8 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 4% that might be because of the non-idealities of the CFOA.

a) 4.3.2 Band Pass

For selected values of passive components: fo=1.59KHz , Q=0.707

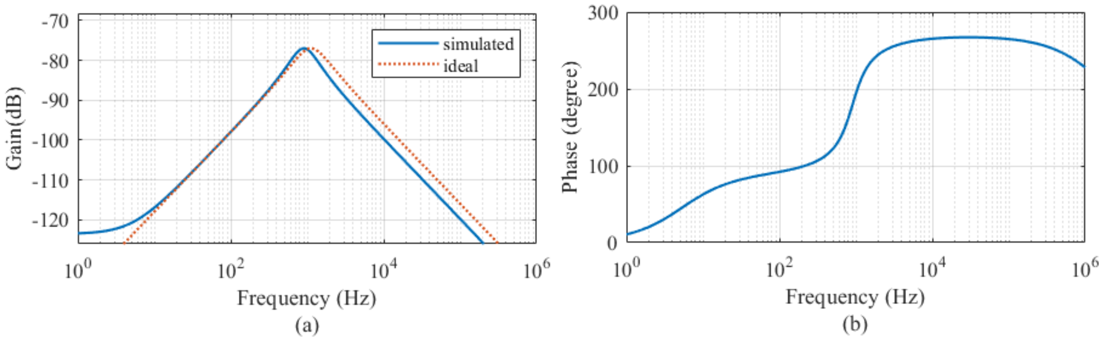


Fig. 4.9 a) Gain Response for ω_o=10^4rad/sec b)Phase Response of BPF

From fig 4.9 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 10% that might be because of the non-idealities of the CFOA.

4.3.3 Low pass

For selected values of passive components: f_o=1.59KHz , Q=0.707

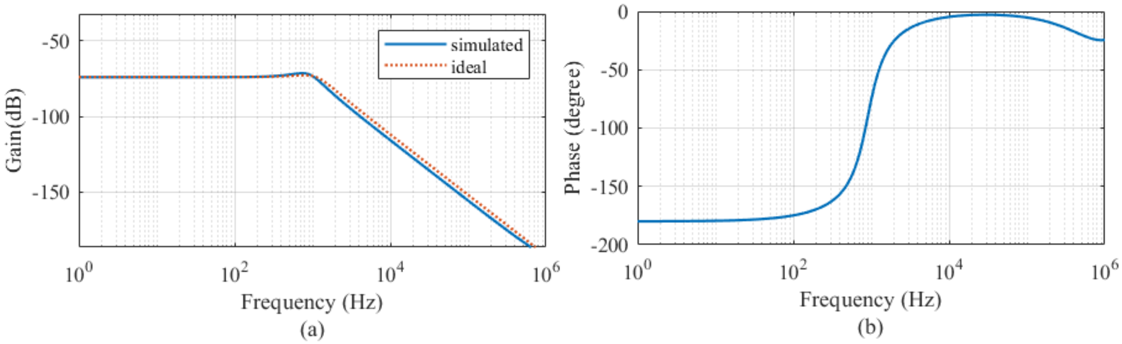


Fig. 4.10 a) Gain Response for f_o=1.59KHz b)Phase Response of LPF

From fig 4.10 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 8% that might be because of the non-idealities of the CFOA.

Table 4.3 Comparison table between simulated and theoretical values of TAM

Filter Type	Designed Frequency(kHz)	Simulated Frequency(kHz)	%Error
HPF	1.59	1.533	3.61
BPF	1.59	1.435	9.72
LPF	1.59	1.473	7.38

4.4. Transimpedance Mode

4.4.1 High Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707

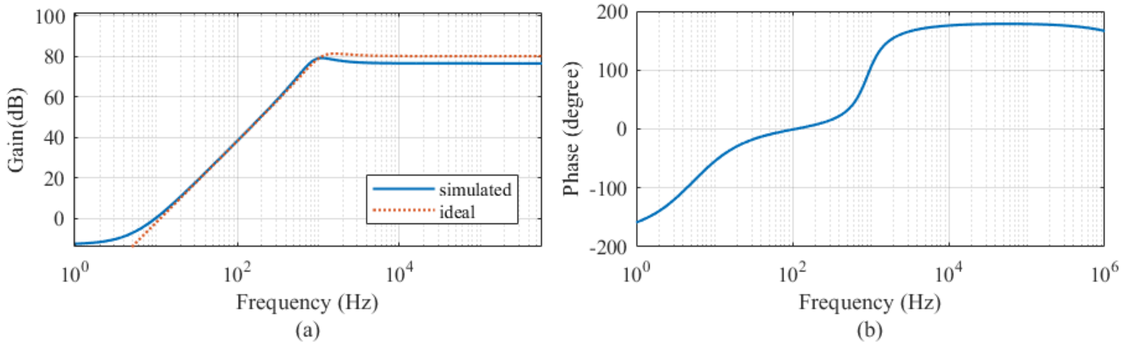


Fig. 4.11 a) Gain Response for f_o=1.59KHz b)Phase Response of HPF

From fig 4.11 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 6% that might be because of the non-idealities of the CFOA.

4.4.2 Band Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707

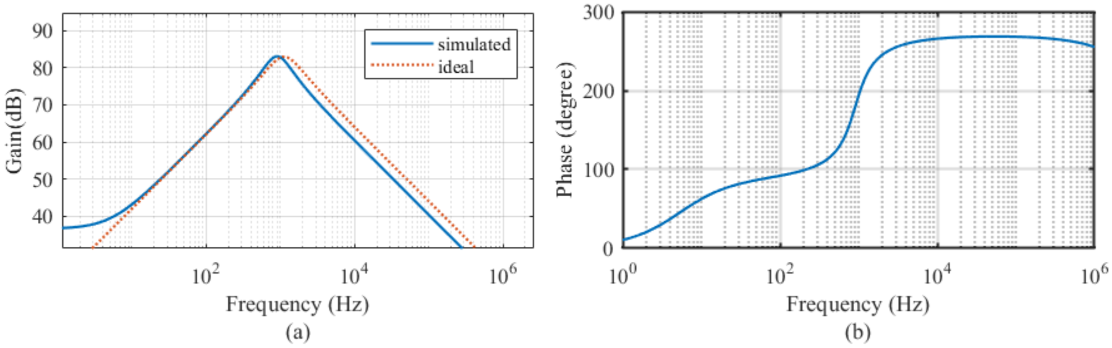


Fig. 4.12 a) Gain Response for f_o=1.59KHz b)Phase Response of BPF

From fig 4.12 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 8% that might be because of the non-idealities of the CFOA.

4.4.3 Low Pass

For selected values of passive components: f_o=1.59KHz , Q=0.707

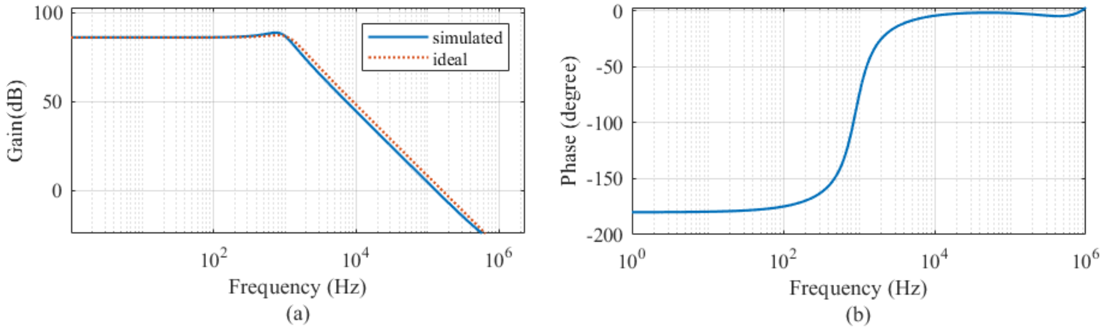


Fig. 4.13 a) Gain Response for f_o=1.59KHz b)Phase Response of LPF

From fig 4.14 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 5% that might be because of the non-idealities of the CFOA.

4.4.4 Band Reject

For selected values of passive components: f_o=1.59KHz , Q=0.707

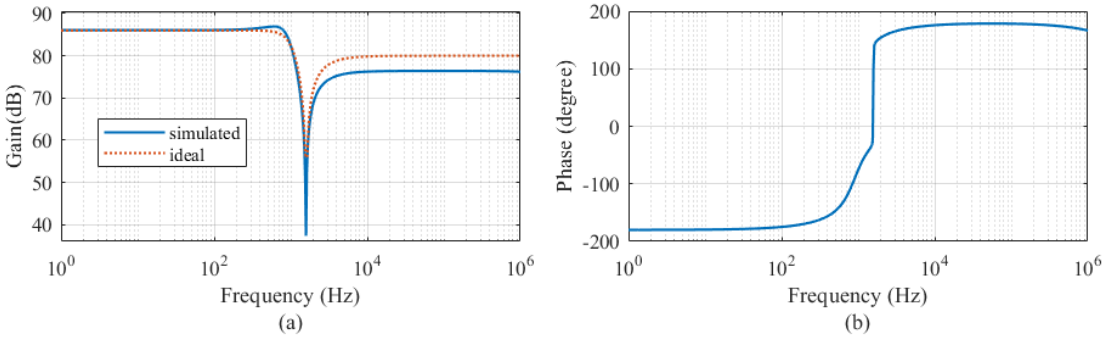


Fig. 4.14 a) Gain Response for f_o=1.59KHz b)Phase Response of BRF

From fig 4.14 it can be inferred that simulated cutoff/pole frequency is almost the same as theoretical frequency. There is an error of less than 3% that might be because of the non-idealities of the CFOA.

Table 4.4 Comparison table between simulated and theoretical values of TIM

Filter Type	Designed Frequency(kHz)	Simulated Frequency(kHz)	%Error
HPF	1.59	1.504	5.39
BPF	1.59	1.468	7.66
LPF	1.59	1.513	4.86
BSF	1.59	1.557	2.08

CHAPTER 5

CONCLUSION

A novel CFOA based mixed-mode biquad filter has been introduced in this work.

In chapter 1, CFOA and active filters circuits are introduced. There is discussion of the benefits of CFOAs, including its large bandwidth, high slew rate and excellent high frequency performance. It also explains the necessity of mixed mode filters in modern analog signal processing applications. Additionally, the motivation for the suggested CFOA based mixed mode biquad active filter is presented.

A thorough analysis of the literature on first order and second order CFOA based filter designs is provided in chapter 2. The benefits, drawbacks and practical implementation elements of several previously published VM, CM, TAM and TIM universal filters are covered. The suggested mixed mode biquad filter is inspired by the identified research gap.

Chapter 3 presents the fundamental idea and features of the CFOA as well as the suggested CFOA based mixed mode filter topology. The transfer functions for four modes are derived theoretically and expressions for resonance frequency, quality factor and bandwidth are obtained.

In chapter 4, OrCAD Pspice simulations based on AD844 CFOA macro models are used to validate the proposed filter. The HP, LP, BP and BR filters' magnitude and phase responses in various operating modes are shown.

REFERENCES

---

[1] Dogan, Mehmet, Erkan Yuce and Zafer Dicle. “CFOA-based first-order voltage-mode universal filters.” AEU-International Journal of Electronics and Communication 161 (2023): 154550.

[2] D.R. Bhaskar, A Raj, R Senani and P Kumar, “CFOA-based simple mixed mode first order universal filter configurations” Int. J Circuit Theory Appl., vol. 50, pp. 2631-2641, 2022.

[3] Raj, Ajishek, Data Ram Bhaskar, Raj Senani, and Pragati Kumar "Extension of recently proposed two-CFOA-GC all pass filters to the realisation of first order universal active filters." AEU-International Journal of Electronics and Communications 146 (2022): 154119.

[4] Nako, Julia, Costas Psychalinos, and Shahram Minaei. “First-order universal shadow filter design with scaled time constants.” International Journal of Circuit Theory and Applications 52.8 (2024): 4040-4053

[5] S.I. Liu and D.-S. Wu, “New current feedback amplifier based universal biquadratic filter,” IEEE Trans. Instrum. Meas., vol. 44, no. 4, pp. 915-917, 1995.

[6] M.T. Abuelma’atti and S.M. Al-Shahrani, “New universal filter using two current feedback amplifiers ,” Int. J. Electron., vol. 80, no. 6, pp. 753-756, 1996.

[7] Horng, and Lee. “High input impedance voltage-mode lowpass, bandpass and highpass filter using current-feedback amplifiers.” Electronics Letters 33.11 (1997): 847-948

[8] Horng, Jiun-Wei. “Voltage-mode multifunction filter using one current feedback amplifier and one voltage follower.” International journal of electronics 88.2 (2001): 153-157.

[9] Horng, Jiun-Wei. “New configuration for realizing universal voltage-mode filter using two current feedback amplifiers.” IEEE Transactions on Instrumentation and Measurement 49.5 (2000): 1043-1045

[10] Nikoloudis, Sotiris, and Costas Psychalinos. “Multiple input single output universal biquad filter with current feedback operational amplifier” Circuits, Systems and Signal Processing 29.6 (2010): 1167-1180.

[11] Bhaskar, Ajishek Raj, and Raj Senani. “Three new CFOA-based SIMO-type universal active filter configurations with unrivalled features.” AEU-International Journal of Electronics and Communications 153 (2022): 154285.

[12] Chen, Hua-Pin, San-Fu Wang, Yitsen Ku, An-Chun Yeh, and Yu-Hsi Chen. “Design of second-order multifunction filter IC based on current feedback amplifiers with independent voltage gain control.” IEEE Access, 10, 63301-63313.

[13] HP Chen, IC Wey, LY Chen, Wu CY, SF Wang “Design and verification of a new universal active filter based on the current feedback operational amplifier and commercial AD844 integrated circuit.” Sensors 23.19 (2023): 8258.

[14] M Dogan, E Minayi, Yuce E, Minaei S “ Current feedback operational amplifier-based fully orthogonal universal and multifunction filters.” International Journal of Circuit Theory and Applications 52.8 (2024): 4086-4104

[15] SS Gupta, DR Bhaskar, R Senani, AK Singh “Inverse active filters employing CFOAs.” Electrical Engineering 91.1 (2009): 23-26

[16] Tangsrirat, Worapong, and Wanlop Surakampontorn. “Single- resistance-controlled quadrature oscillator and universal biquad filter using CFOAs.” AEU-International Journal of Electronics and Communications 63.12 (2009): 1080-1086.

[17] Yuce, Erkan, and Shahram Minaei. “Universal current-mode filters and parasitic impedance effects on the filter performances.” International Journal of Circuit Theory and Applications 36.2 (2008): 161-171.

[18] R Senani, D.R. Bhaskar, and P Kumar. “Two-CFOA-grounded-capacitor first-order all-pass filter configurations with ideally infinite input impedance.” AEU-International Journal of Electronics and Communications 137 (2021): 153742

[19] Dogan, Mehmet, Erkan Yuce, and Shahram Minaei. “An Approach to CFOA-based Second-Order Universal Filters.” Elektronika ir Electrotechnika 31.3 (2025): 22-29

[20] A.K. Singh and R. Senani. “CFOA based state variable biquad and its high frequency compensation..” IEICE Electron. Express, vol. 2, no. 7, pp. 232-238, 2005.

[21] V.K. Singh, A.K. Singh, D.R. Bhaskar, and R. Senani, “ Novel mixed-mode universal biquad configuration,” Electron. Express, vol. 2, no. 22, pp. 548-553, 2005.

[22] S.-F. Wang, H.-P. Chen, Y. Ku, and P.-Y. Chen, “ A CFOA-based voltage-mode multifunction biquadratic filter and quadrature oscillator,” Applied Sciences, vol. 9, no. 11, 2019.

[23] DR Bhaskar, M Shrivastava, A Raj, and P Kumar. “Floating parallel lossy inductance, parallel lossy capacitance, parallel C-D, and lossless capacitance multiplier circuits using current feedback operational amplifiers.” International Journal of Circuit Theory and Applications 52.3 (2024): 1489-1517.

[24] AA Tammam, K. Hayatleh, M. Ben-Esmael, N. Terzopoulos, and Cristiana Sebu. “Critical review of the circuit architecture of CFOA,” Int. J. Electron., vol. 101, no. 4, pp. 4411-451, 2014.

[25] S. Nikoloudis and C. Psychalinos, “Multiple-input single-output universal biquad filter with CFOAs," Circuits Syst. Signal Process., vol. 29, pp. 1167-1180, 2010.

[26] H. Alpaslan, “Second-order mixed-mode multi-input single-output universal filter using three CFOAs,” Circuits, Systems, and Signal Processing, vol. 44, pp. 8027-8068, 2025.

[27] Soliman, Ahmed M., and Ahmed H. Madian. “MOS-C KHN filter using voltage op amp, CFOA, OTRA and DCVC.” Journal of Circuits, Systems and Computers 18.04 (2009): 733-769.

[28] E. Yuce, “Fully integrable mixed-mode universal biquad with specific application of the CFOA,” AEU-Int. J. Electron. Commun., vol. 64, pp. 304-309, 2010.

[29] Liu, S-I. “Universal filter using two current-feedback amplifiers.” Electronics Letters 31.8 (1995): 629-630

[30] R Senani, and S.S. Gupta. “Universal voltage-mode/current-mode biquad filter realised with current feedback op-amps.” Frequenz 51.7-8 (1997): 203-208

[31] R Senani , A Raj, DK Srivastava, DR Bhaskar “A two-CFOA-based multi-function circuit.” AEU-International Journal of Electronics and Communications 189 (2025): 155602.

[32] Raj Senani. “Realization of a class of analog signal processing/signal generation circuits: Novel Configurations using current feedback op-amps.” Frequenz 52.9-10 (1998): 196-206.

[33] Shah, Nisar Ahmad, Syed Zaffer Iqbal, and Mohammad Farooq Rather. “Versatile voltage-mode CFA-based universal filter.” AEU-International Journal of Electronics and Communications 59.3 (2005): 192-194.

[34] Shah, Nisar Ahmad, and Mohd Amin Malik. “New high input impedance voltage-mode lowpass, bandpass and highpass filter using current feedback amplifiers.” Journal of Circuits, Systems, and Computers 14.06 (2005): 1037-1043

[35] Shah, Nisar Ahmad, and Mohmad Amin Malik. “Voltage/current-mode universal filter using FTFN and CFA.” Analog Integrated Circuits and Signal Processing 45.2 (2005): 197-203.

[36] N.A Shah, and M.F. Rather. “Design of Voltage-Mode, Trans-Admittance-Mode, Trans-Impedance-Mode and Current-Mode Biquad Filters Employing Plus Type Current Feedback Amplifiers.” Journal of Active & Passive Electronic Devices 5 (2010).

[37] R.K. Sharma, and R. Senani. “Multifuction CM/VM biquads realized with a single CFOA and grounded capacitors.” AEU-International Journal of Electronics and Communications 57.5 (2003): 301-308.

[38] R.K. Sharma, and R. Senani. “Universal current mode biquad using a single CFOA.” International Journal of Electronics 91.3 (2004): 175-183.

[39] VK Singh, AK Singh, DR Bhaskar, R Senani “New universal biquads employing CFOAs.” IEEE Transactions on Circuits and Systems II: Express Briefs 53.11 (2006): 1299-1303.

[40] VK, Singh. “Novel mixed-mode universal biquad configurations.” IEICE Electronics Express 2.22 (2005): 548-553.

[41] Soliman, Ahmed M. “Applications of the current feedback operational amplifiers.” Analog Integrated Circuits and Signal Processing 11.3 (1996): 265-302

[42] Topaloglu, S.E.R.K.A.N., M.E.H.M.E.T. Sagbas, and F. Anday. “Three-input single-outtput second-order filters using current-feedback amplifiers.” AEU-International Journal of Electronics and Communications 66.8 (2012): 683-686.

[43] Wang HY, Chang SH, Yang TY, Tsai PY . “A Novel Multifunction CFOA-Based Inverse Filter.” Circuit Syst. 2.1 (2011): 14-17.

[44] SF Wang, HP Chen, Y Ku, YF Li. “High-input impedance voltage-mode multifunction filter.” Applied Sciences 11.1 (2021): 387.

[45] Wu DS, Lee HT, Hwang YS, Wu YP “CFA-based universal filter deduced from a Mason graph.” International journal of electronics 77.6 (1994): 1059-1065.

[46] Bhaskar, Ajishek Raj, and Pragati Kumar. “Mixed-mode universal biquad filter using OTAs.” Journal of Circuits, Systems and Computers 29.10 (2020): 2050162.

[47] F. Yucel and E. Yuce. “Supplementary CCII based second-order universal filter and quadrature oscillators.” AEU- International Journal of Electronics and Communications.

[48] Devanshu Saxena, Garima Mann and Chaudhry Indra Kumar. “Voltage-Mode Biquad Filter Using Single VDCC.” 2024 4th International Conference on Advancement in Electronics and Communication Engineering (AECE) (2024): 544-548

[49] Koson Pitaksuttayaprot, Somkid Ritnathikul and W. Jaikla. “Voltage-Mode Biquad Multifunction Filter Using VCiis.” 2022 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS) (2022): 1-4.

[50] Arslanalp R. “A Novel DDCC-Based Current-Mode Two-Integrator-Loop Active-C Biquad.” J. Circuits Syst. Comput., 32 (2022): 2350140:1-2350140:18.

[51] Kulapong W, Siripongdee S, Jaikla W. “Design of Second Order Lowpass and Bandpass Filter Using Single VDDDA and Its Modification as Sinusoidal Oscillator.” 2019 2nd World Symposium on Communication Engineering (WSCE) (2019): 152-156.

[52] Thinthaworn K, Jaikla W, Suwanjan P, Adhan S, Srichaiya N, Kwawsibsame A, Khateb F “A Compact Electronically Controllable Biquad Filter Synthesizing from Parallel Passive RLC Configuration.” 2020 59th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE) (2020):903-907.

[53] Natchanai Roongmuanpha, P. Mongkolwai, T. Pukkalanun and W. Tangsrirat. “Dual-Mode Biquadrartic Filter Employing Second-Generation Voltage Conveyors.” Proceedings of the 2024 13th International Conference on Informatics, Environment, Energy and Applications (2024).

[54] W. Jaikla, Surapong Siripongdee and P. Suwanjan. “Realization of Voltage-mode Multifunction Biquadratic Filter Using Minimum Number of Active Element.” IOP Conference Series: Materials Science and Engineering, 559 (2019).

[55] D. Bhaskar, V.K. Sharma, M. Monis and S.M.I. Rizvi. “New current-mode universal biquad filter.” Microelectronics Journal, 30 (1999): 837-839.

[56] A. Fabre and M. Alami. “Universal current mode biquad implemented from two second generation current conveyors.” IEEE Transactions on Circuits and Systems I-regular Papers, 42 (1995): 383-385

[57] N. Pandey, R. Pandey, Rashika Anurag and R. Vijay.” A Class of Differentiator-Based Multifunction Biquad Filters Using OTRAs.” Advances in Electrical and Electronic Engineering, 18 (2020): 31-40

[58] A Raj,DR Bhaskar, P Kumar. “Multiple-input single-output universal biquad filter using single output OTAs.” In2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES) 2018 Oct 22 (pp. 1237-1240). IEEE.

[59] Surachet Chinnapark et al. “Resistorless Transconductance-mode Multifunction Filter with Orthogonal and Electronic Tune of Natural Frequency and Quality Factor.” 2022 International Electrical Engineering Congress (iEECON) (2022): 1-5.

[60] Mehmet Dogan and E. Yuce. “A Voltage-mode fully cascadable biquad with three CFOAs and grounded capacitors.” AEU-International Journal of Electronics and Communications (2024).

[61] KB Singh, M Joshi, Ranjan A. “An MOS-C Multifunction Filter Employing DXCCTA for High-Frequency Operation.” (2020): 133-142.

[62] Prakhar Bhardwaj, Harsha Sharan and Amit Saxena “CMOS LAYOUT DESIGN FOR OTA-C BIQUAD FILTER..” International Conference on Approximate Reasoning, 6 (2018): 393-398.

[63] W. Jaikla. “Electronically Controllable Voltage-mode Multifunction Biquad Filter with High-Input and Low-Output Impedance for Biomedical Signal Processing.” 2024 8th International Conference on Biomedical Engineering and Applications (ICBEA) (2024): 146-150.

[64] Suvajit Roy, Tapas Kumar Paul, Saikat Maiti and R. Pal. “ Voltage Differencing Current Conveyor Based Voltage-Mode and Current-Mode Universal Biquad Filters with Electronic Tuning Facility.” International Journal of Engineering and Technology Innovation, 11 (2021): 146-160

[65] Sirigul Bunrueangsak, W. Jaikla, A. Chaichana, Piya Supavarasuwat, Surapong Siripongdee and P. Suwanjan. “Synthesis of electronically tunable multifunction biquad filter using voltage differencing differential input buffered amplifiers.” ETRI Journal, 47 (2024): 144-157

[66] A Raj, P Kumar, DR Bhaskar. “ Multiple-Input Single-Output Universal Biquad Filters Using Reduced Number of OTAs.” 2019 International Symposium on Advanced Electrical and Communication Technologies (ISAECT) (2019): 1-4.

[67] SV Singh, RS Tomar, DS Chauhan “ Single CFTA Based Current-Mode Universal Biquad Filter.” The Journal of Engineering Research, 13 (2016): 172-186.

[68] Shankar C, Singh SV, Imam R. “ SIFO-VM/TIM universal biquad filter using single DVCCTA with fully CMOS realization.” Analog Integrated Circuits and Signal Processing, 109 (2021): 33-46.

[69] AR Ismael “ THE APPLICATIONS EMPLOYED TO DESIGN A NEW KIND OF FILTER USING THE ACTIVE ELEMENT (VDBA).” (2017).

[70] A. Gupta, “ CFOA-based integrators: A comparative study of the classical two-CFOA realization and a new single-CFOA version,” Aegaeum Journal, vol. 10, no. 8, pp. 27-49, 2022