9 TH ORDER BUTTERWORTH LOW PASS FILTER DESIGN

A report submitted to the

Department of Electrical and Information Engineering
Faculty of Engineering
University of Ruhuna Sri Lanka

On 13th of March 2023

In completing an assignment for the module
EE5207 Electronic Circuit Design

By

Group 5

KHEMINDA D. A. J. P. - EG/2019/3636
LIYANAGE D. L. S. B. - EG/2019/3655
SADEEPA P. M. A. S. - EG/2019/3726

ABSTRACT

This report presents the design, implementation, and performance evaluation of a 9th Order Butterworth Low Pass Filter, an essential component for processing signals in many electronic circuits. The report consists of four chapters, starting with an overview of the filter's specifications and design requirements in the first chapter. The second chapter details the design calculations and performance analysis, including the cutoff frequency, passband ripple, and stopband attenuation of the filter. The third chapter provides practical implementation details, including the selection and integration of key components and construction guidelines. Finally, the fourth chapter presents the results of the performance testing, including measurements of the filter's frequency response, passband ripple, and stopband attenuation. Overall, this report provides a comprehensive understanding of the design, implementation, and performance of a 9th Order Butterworth Low Pass Filter, suitable for a wide range of signal processing applications.

PREFACE

This report presents the preface for the module EE5207, Electronic Circuit Design, which required the design and implementation of a 9th Order Butterworth Low Pass Filter with a cutoff frequency of 1 kHz. The project builds on the fundamental knowledge obtained from the modules EE2202 Introduction to Electronic Engineering and EE3301 Analog Electronics, and further information was obtained from online resources and books. The preface outlines the design methodology, component selection, circuit implementation, and testing procedures of the 9th Order Butterworth Low Pass Filter. The project aims to provide a comprehensive understanding of the design and operation of a 9th Order Butterworth Low Pass Filter, suitable for processing signals in a range of electronic applications. The project was completed under the guidance of Dr. Subodha Gunawardena, module coordinator of EE5207, W.G.C.A. Sankalpa lecturer of EE5207 and G.C.W. Thilakarathne lecturer of EE5207 at the Faculty of Engineering, University of Ruhuna.

CONTENT

LIST OF FIGURES

1 CHAPTER 01 - INTRODUCTION

1.1 INTRODUCTION

In the field of electronic circuit design, a filter is a crucial component that can selectively pass or amplify certain frequencies while suppressing or attenuating others. This makes it possible to extract important frequencies from signals while removing unwanted or irrelevant ones. The focus of this project, which falls under the purview of EE5308 Electronic Circuit Design, is on designing a 9th order Butterworth low pass filter with a cut off frequency of 15 kHz. A low pass filter is a type of filter that can reshape, modify or reject high frequencies in an electrical signal while passing signals that contain low frequencies. Cut-off frequency is a critical parameter that defines the filter's boundary. It is the frequency at which the energy going through a system begins to be attenuated, rather than passing through it. For this project, the cut off frequency is set at 15 kHz. The Butterworth filter is a signal processing filter with a passband frequency response that is as flat as possible, i.e., with no ripples. The Butterworth low pass filter is designed to pass low frequencies lower than the cut off frequency while attenuating the frequency components above the cut-off frequency.

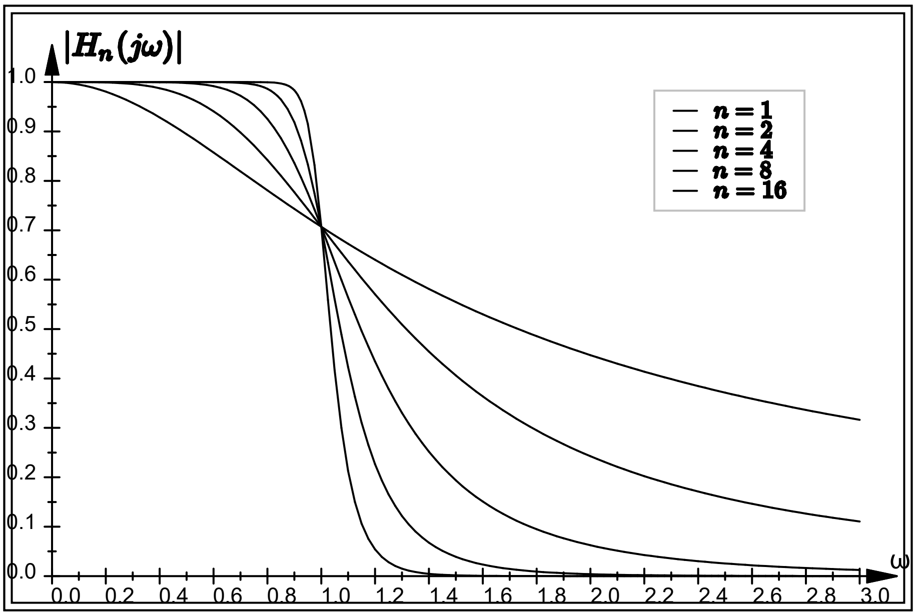

Figure 1 : Frequency response of a Butterworth Low pass filter

1.2 OPERATION OF 9TH ORDER BUTTERWORTH LOW PASS FILTER

A 9th order Butterworth low pass filter is designed to attenuate high frequency components of an electrical signal while allowing low frequency components to pass through. The filter works by using a combination of capacitors and inductors to create a frequency-dependent impedance that selectively filters out high-frequency signals. The Butterworth filter is designed to have a maximally flat frequency response within the passband, meaning that it has minimal attenuation of signals within the passband. In the case of a 9th order Butterworth low pass filter with a cut-off frequency of 10 kHz, signals with frequencies below 15 kHz will be passed through with minimal attenuation, while frequencies above 15 kHz will be attenuated. The order of the filter determines the slope of the transition between the passband and the stopband, with higher-order filters having steeper transitions. In general, the design of a Butterworth filter involves selecting the desired cut-off frequency, determining the filter order, and calculating the values of the capacitors and inductors needed to implement the filter circuit.

1.3 APPLICATION OF 9TH ORDER BUTTERWORTH LOW PASS FILTER

A 9th order Butterworth low pass filter has various applications in electronic circuits where high-frequency signals need to be filtered out while preserving low-frequency signals. Some common applications include audio processing, signal conditioning, and communications systems. For instance, in audio processing, a 9th order Butterworth low pass filter can be used to eliminate unwanted high-frequency noise and distortion while preserving the quality of the low-frequency audio signals. In signal conditioning, the filter can be used to remove high-frequency interference from signals that are susceptible to noise, such as medical or scientific instrumentation. In communication systems, the filter can be used to suppress high-frequency harmonics and spurious signals that may cause interference with other systems. Overall, a 9th order Butterworth low pass filter is a versatile tool for frequency selective filtering and can be used in a wide range of electronic applications.

1.4 PROBLEM STATEMENT

According to the project task, we design a 9 th order Butterworth low pass filter that the cut -off frequency is 15kHz.

1.5 OBJECTIVES

1. To provide a detailed explanation of the design process for a 9th order Butterworth low pass filter and its application in electronic circuits.
2. To analyze the performance of the filter in terms of its frequency response, phase shift, and attenuation characteristics, using theoretical calculations and simulation tools.
3. To discuss the selection of key components such as resistors, capacitors, and operational amplifiers based on their specifications and performance requirements.
4. To present the practical implementation of the filter, including the schematic diagram, printed circuit board (PCB) layout, and construction guidelines.
5. To evaluate the filter's performance using laboratory measurements and compare them with theoretical predictions and simulation results.
6. To discuss the limitations and trade-offs associated with the design of a high-order filter, including component tolerances, noise, and distortion.
7. To explore the potential applications of the filter in electronic systems, such as audio processing, signal conditioning, and communication systems.
8. To provide recommendations for future improvements and modifications to the filter design, based on the limitations and performance requirements of specific applications.
9. To demonstrate a comprehensive understanding of the design, implementation, and performance evaluation of a 9th order Butterworth low pass filter, suitable for a range of electronic applications.

1.6 METHODOLOGY

1. Study the 9th order Butterworth low pass filter.
2. Study the practical implementation of the 9th order Butterworth low pass filter.
3. Gather information about the UA 741 Op-amps.
4. Prepare necessary calculations to obtain the required capacitors and resistor values.
5. Design the 9th order Butterworth low pass filter using the Proteus simulator.
6. Test the Proteus design schematics on a breadboard.
7. Implement the 9th order Butterworth low pass filter design using the PCB circuit design method.

2 CHAPTER 02 - CALCULATION

2.1 CIRCUIT TOPOLOGY

The 9th order Butterworth low pass filter can be decomposed to a 1 st order low pass filter stage followed by four cascaded 2nd order active low pass filters.

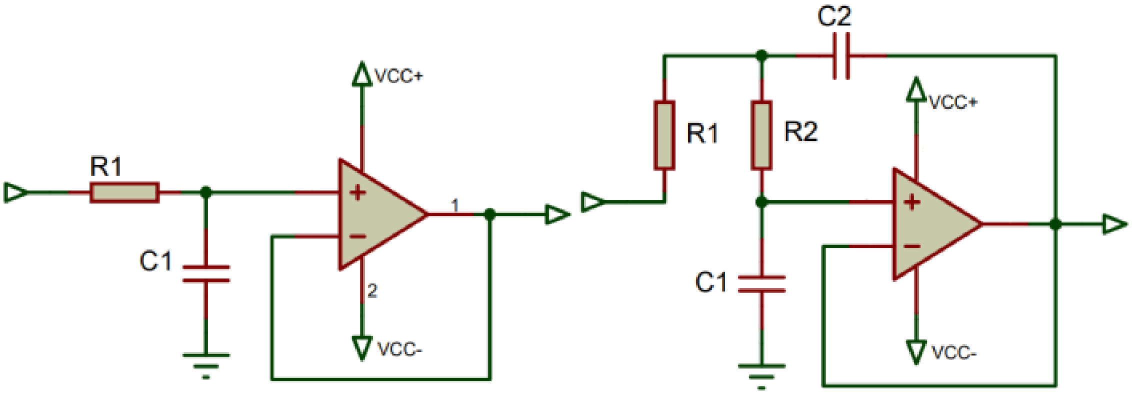

Figure 2 : Component Arrangement of First order Low pass filter stage (Left) and 2nd Order Low pass Butterworth Filter

2.2 CALCULATIONS

- For stage 1 (Figure 1 left)

$$\mathrm{R}_1 = \left(\frac{a_1}{\omega c_1}\right) \ldots\ldots\ldots\ldots\ldots (01)$$

- For Stage 2,3,4 and 5 (Figure 1 right)

$$C_2 \geq C_1 * 4 * \frac{b_1}{a_1^2} \ldots\ldots\ldots\ldots\ldots\ldots (02)$$

$$R_1 = \frac{a_1 * c_2 - \sqrt{(a_1 * c_2)^2 - 4 * b_1 * c_1 * c_2}}{4\pi * f * c_1 * c_2} \ldots\ldots\ldots\ldots\ldots\ldots (03)$$

$$R_2 = \frac{a_1 * c_2 - \sqrt{(a_1 * c_2)^2 - 4 * b_1 * c_1 * c_2}}{4\pi * f * c_1 * c_2} \ldots\ldots\ldots\ldots\ldots\ldots (04)$$

f = 15 kHz and a1 and b1 coefficients were obtained by Butterworth filter design table.

- **Stage 1**

$a_1 = 1.000$

$b_1 = 0.000$

$c = 10\ nF$

From equation 01,

$$R_1 = \frac{1}{2\pi * 15 * 10^3 * 10 * 10^{-9}}\,\Omega$$

$$R_1 = 1061.032\ k\Omega$$

$$\underline{\underline{R_1 = 1\ k\Omega}}$$

- **Stage 2**

$a_2 = 1.8794$

$b_2 = 1.0000$

$c = 15\ nF$

From equation 02,

$$C_2 \geq\ \ 15 * 10^{-9} * 4 * \frac{1}{1.8794^2}\,\mathrm{F}$$

$$C_2 \geq\ \ 16.99 * 10^{-9}\ F$$

$$\underline{\underline{C_2 =\ 27\ \ nF}}$$

From Equation 03,

$$R_1 = \frac{1.8794 * 27 * 10^{-9} - \sqrt{(1.8794 * 27 * 10^{-9})^2 - 4 * 15 * 27 * 10^{-18}}}{4\pi * 15 * 10^3 * 15 * 27 * 10^{-18}}\,\Omega$$

$$R_1 = 259.87\Omega$$

$$\underline{\underline{R_1 = 330\ \Omega}}$$

From Equation 04,

$$R_2 = \frac{1.8794 * 27 * 10^{-9} + \sqrt{(1.8794 * 27 * 10^{-9})^2 - 4 * 15 * 27 * 10^{-18}}}{4\pi * 15 * 10^3 * 15 * 27 * 10^{-18}} \Omega$$

$$R_2 = 1069.33\ \Omega$$

$$\underline{\underline{R_2 = 1\ k\Omega}}$$

- **Stage 3**

$a_2 = 1.5321$

$b_2 = 1.0000$

$c = 47\ nF$

From equation 02,

$$C_2 \geq 15 * 10^{-9} * 4 * \frac{1}{1.5321^2} \text{F}$$

$$C_2 \geq 80.09\ nF$$

$$\underline{\underline{C_2 = 82\ nF}}$$

From Equation 03,

$$R_1 = \frac{1.5321 * 82 * 10^{-9} - \sqrt{(1.5321 * 82 * 10^{-9})^2 - 4 * 47 * 82 * 10^{-18}}}{4\pi * 15 * 10^3 * 47 * 82 * 10^{-18}} \Omega$$

$$R_1 = 146.53\ \Omega$$

$$\underline{\underline{R_1 = 220\ \Omega}}$$

From Equation 04,

$$R_1 = \frac{1.5321 * 82 * 10^{-9} + \sqrt{(1.5321 * 82 * 10^{-9})^2 - 4 * 47 * 82 * 10^{-18}}}{4\pi * 15 * 10^3 * 47 * 82 * 10^{-18}} \Omega$$

$$R_2 = 199.29\ \Omega$$

$$\underline{\underline{R_2 = 220\ \Omega}}$$

- **Stage 4**

$a_2 = 1.0000$

$b_2 = 1.0000$

$c = 2.7\ nF$

From equation 02,

$$C_2 \geq \ 2.7 * 10^{-9} * 4 * \frac{1}{1.0000^2}\,\text{F}$$

$$C_2 \geq \ 10.8\ nF$$

$$\underline{\underline{C_2 = \ 56\ nF}}$$

From Equation 03,

$$R_1 = \frac{1 * 56 * 10^{-9} - \sqrt{(1.0000 * 56 * 10^{-9})^2 - 4 * 56 * 2.7 * 10^{-18}}}{4\pi * 15 * 10^3 * 56 * 2.7 * 10^{-18}}\,\Omega$$

$$R_1 = 199.56\ \Omega$$

$$\underline{\underline{R_1 = 220\ \Omega}}$$

From Equation 04,

$$R_1 = \frac{1 * 56 * 10^{-9} + \sqrt{(1.0000 * 56 * 10^{-9})^2 - 4 * 56 * 2.7 * 10^{-18}}}{4\pi * 15 * 10^3 * 56 * 2.7 * 10^{-18}}\,\Omega$$

$$R_2 = 3729 b\Omega$$

$$\underline{\underline{R_2 = 3.3\ k\Omega}}$$

- **Stage 5**

$$a_2 = 0.3473$$
$$b_2 = 1.0000$$
$$c = 4.7\ nF$$

From equation 02,

$$C_2 \geq \ 4.7 * 10^{-9} * 4 * \frac{1}{0.3473^2}\text{ F}$$

$$C_2 \geq \ 155.86 * 10^{-9}\ F$$

$$\underline{\underline{C_2 = \ 220\ nF}}$$

From Equation 03,

$$R_1 = \frac{0.3473 * 27 * 10^{-9} - \sqrt{(0.3473 * 220 * 10^{-9})^2 - 4 * 4.7 * 220 * 10^{-18}}}{4\pi * 15 * 10^3 * 4.7 * 220 * 10^{-18}}\Omega$$

$$R_1 = 180\ \Omega$$

$$\underline{\underline{R_1 = 220\ \Omega}}$$

From Equation 04,

$$R_1 = \frac{0.3473 * 27 * 10^{-9} + \sqrt{(0.3473 * 220 * 10^{-9})^2 - 4 * 4.7 * 220 * 10^{-18}}}{4\pi * 15 * 10^3 * 4.7 * 220 * 10^{-18}}\Omega$$

$$R_2 = 603.6\ \Omega$$

$$\underline{\underline{R_2 = 680\ \Omega}}$$

Table 1: Used C1, C2, R1, R2 values for implementation of 9^{th} order Butterworth low pass filter

Stage	**C1 (nF)**	**C2 (nF)**	**R1 (Ω)**	**R2 (Ω)**
01	10	-	1000	-
02	15	27	330	1000
03	47	82	220	220
04	2.7	56	220	3300
05	4.7	220	220	680

3 CHAPTER 03 – IMPLEMENTATION

3.1 COMPONENTS LIST

RESISTORS

- $1\ \mathrm{k\Omega} \times 2$
- $220\ \Omega \times 4$
- $330\ \Omega \times 1$
- $680\ \Omega \times 1$
- $3.3\ \mathrm{k\Omega} \times 1$

CAPACITORS

- $1\ \mathrm{nF} \times 1$
- $2.7\ \mathrm{nF} \times 1$
- $4.7\ \mathrm{nF} \times 1$
- $10\ \mathrm{nF} \times 1$
- $27\ \mathrm{nF} \times 1$
- $47\ \mathrm{nF} \times 1$
- $56\ \mathrm{nF} \times 1$
- $68\ \mathrm{nF} \times 1$
- $220\ \mathrm{nF} \times 1$

OPAMP

- $\mathrm{UA}\ 741 \times 4$

TBLOCK-12 x 3

3.2 PROTEUS SCHEMATIC CAPTURE

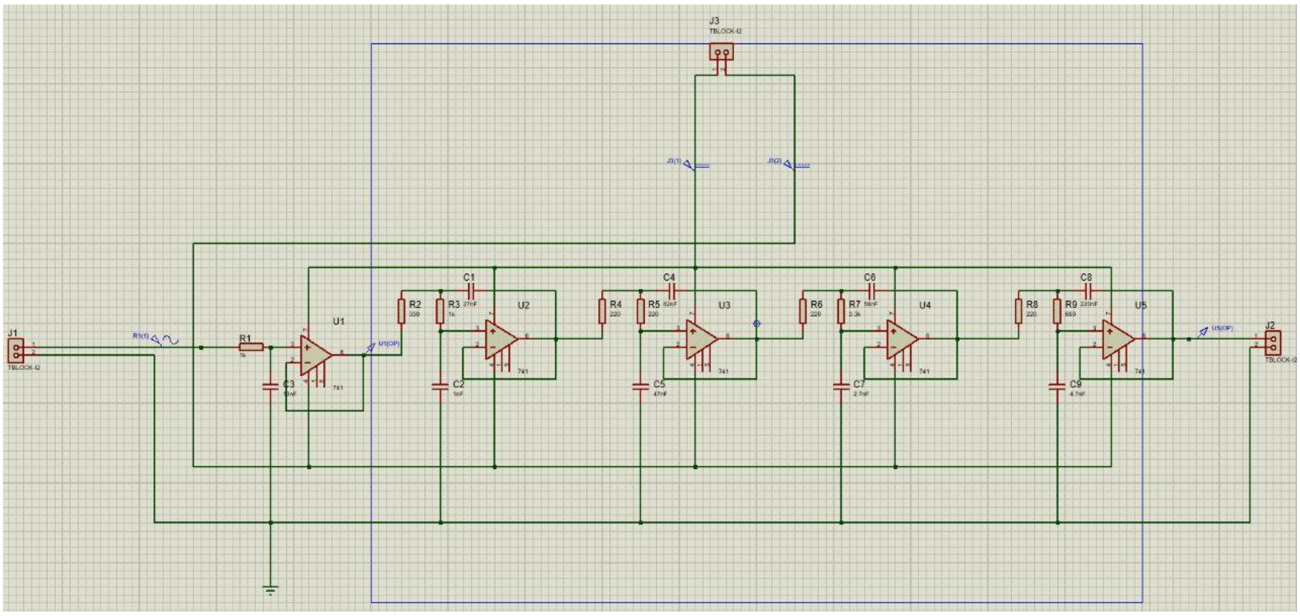

Figure 3 : Proteus Schematic Capture

3.3 PCB LAYOUT

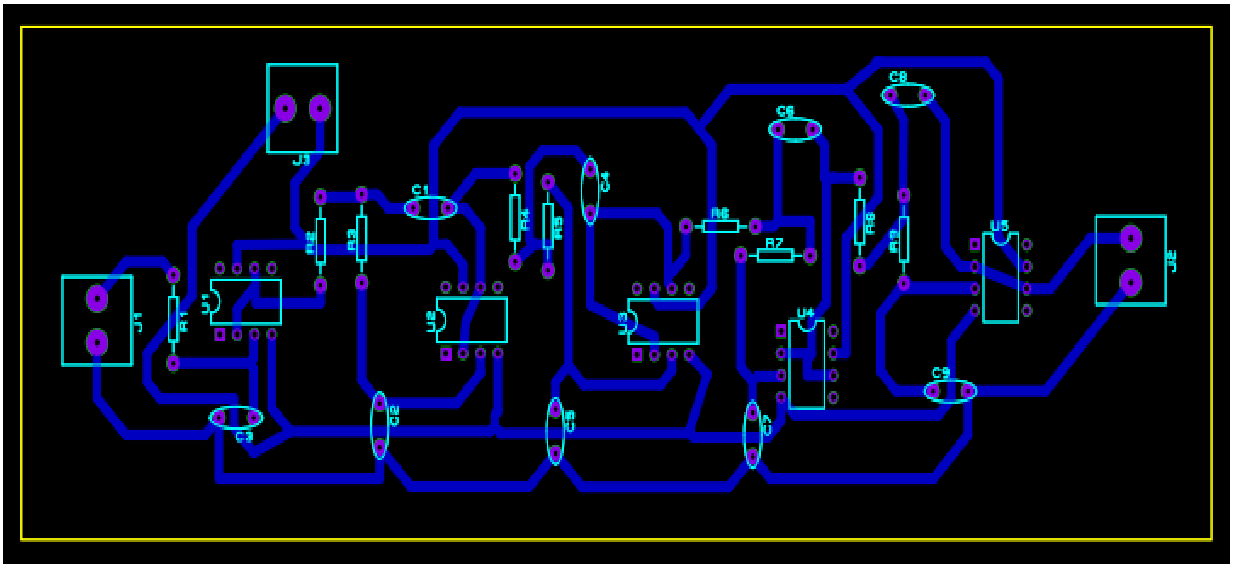

Figure 4 : PCB Layout

3.4 3D VISUALIZATION (TOP VIEW)

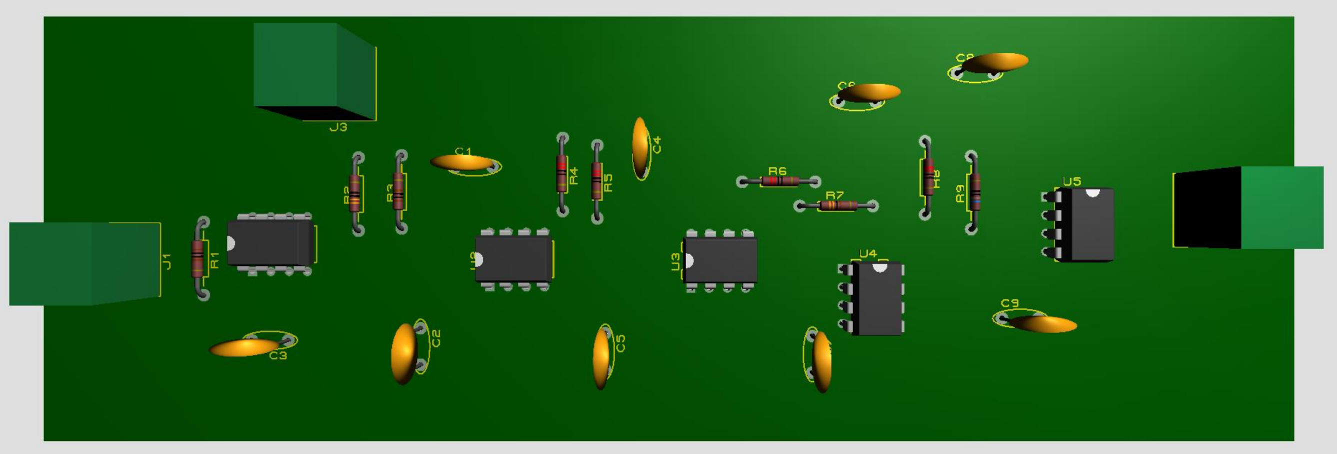

Figure 5 : 3D Visualization (Top View)

3.5 3D VISUALIZATION (BOTTOM VIEW)

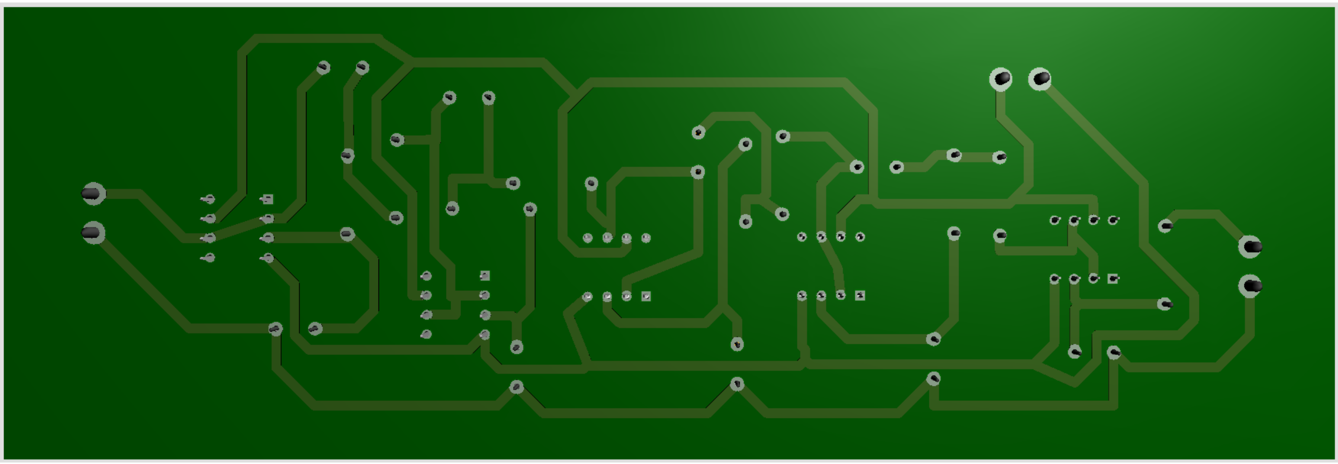

Figure 6 : 3D Visualization (Bottom View)

3.6 IMPLEMENTED CIRCUIT

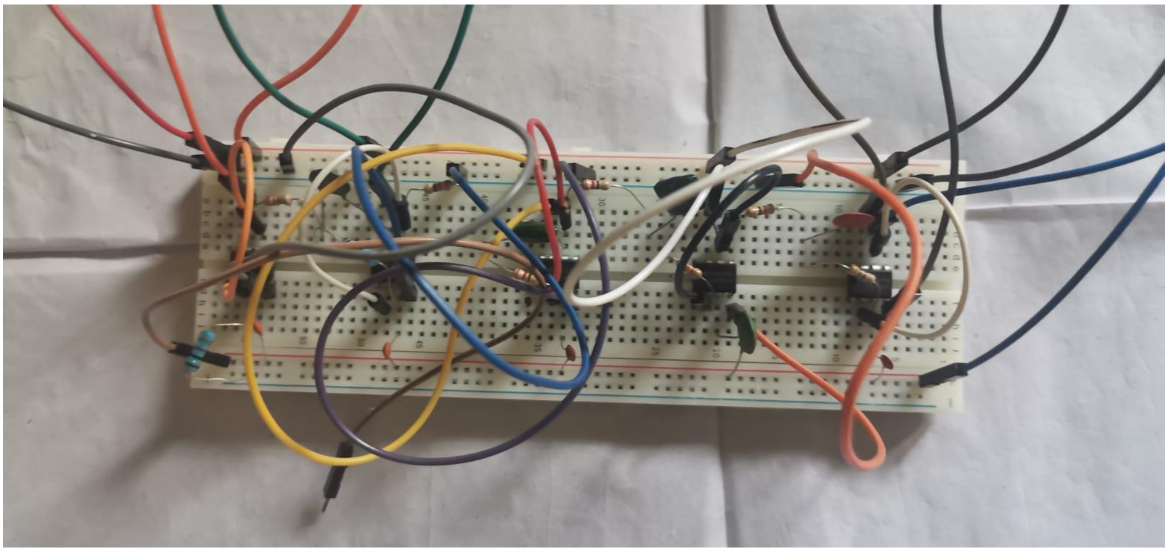

Figure 7 : Practically Implemented circuit using breadboard (Top View)

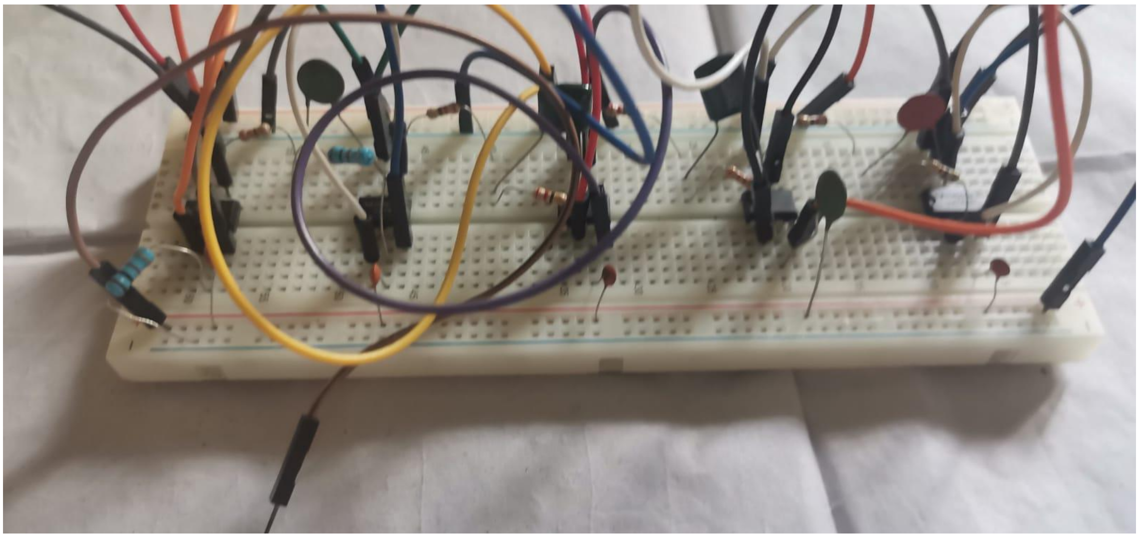

Figure 8 : Practically Implemented circuit using breadboard (Front View)

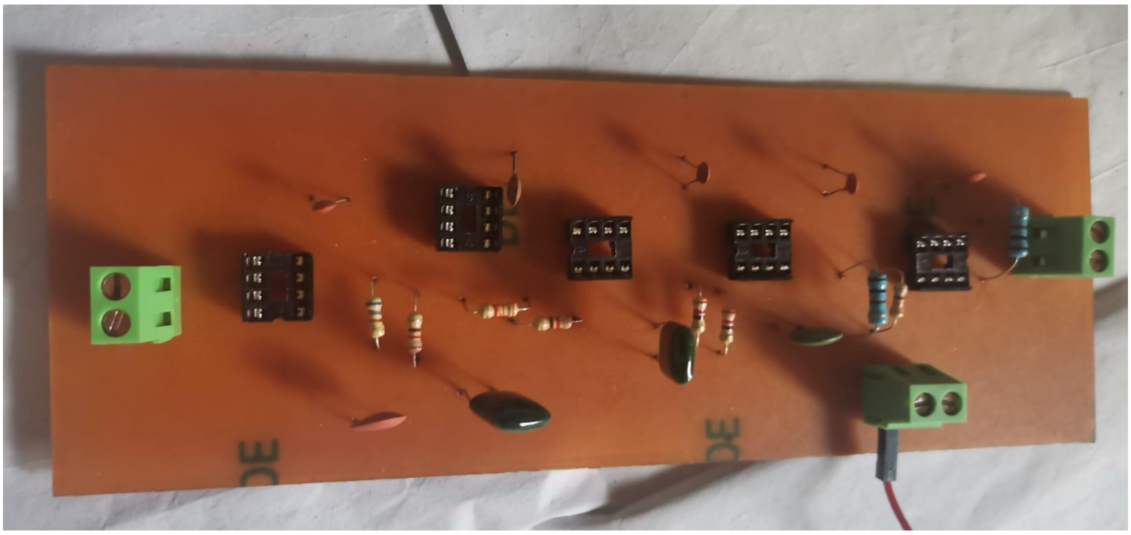

Figure 9 : Top View of the PCB

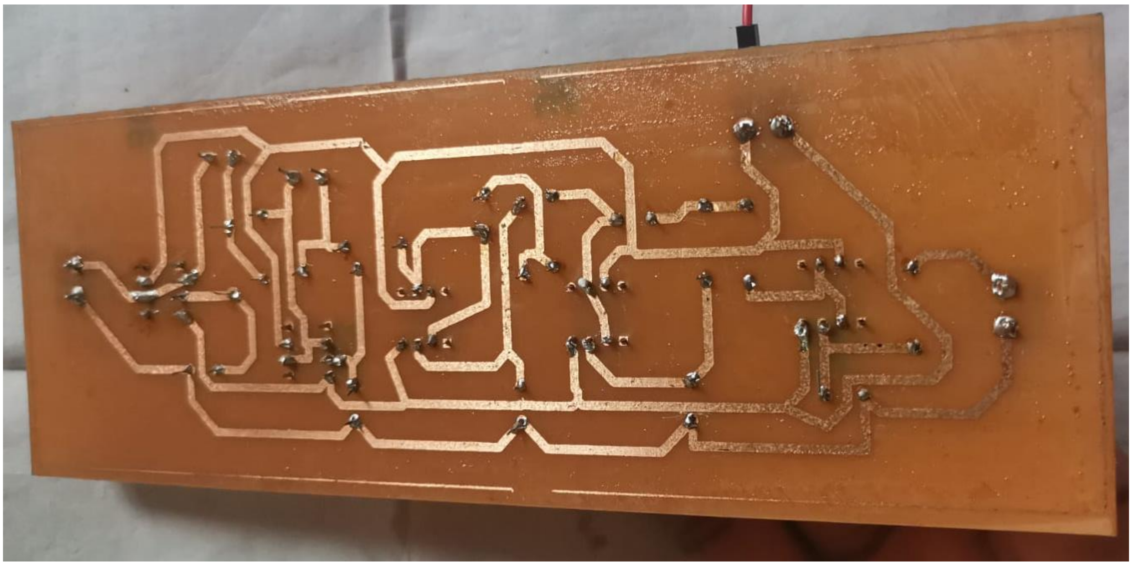

Figure 10 : Bottom View of the PCB

4 CHAPTER 04 – RESULT AND DISCUSSION

4.1 VIRTUAL SIMULATION RESULTS USING PROTEUS SOFTWARE

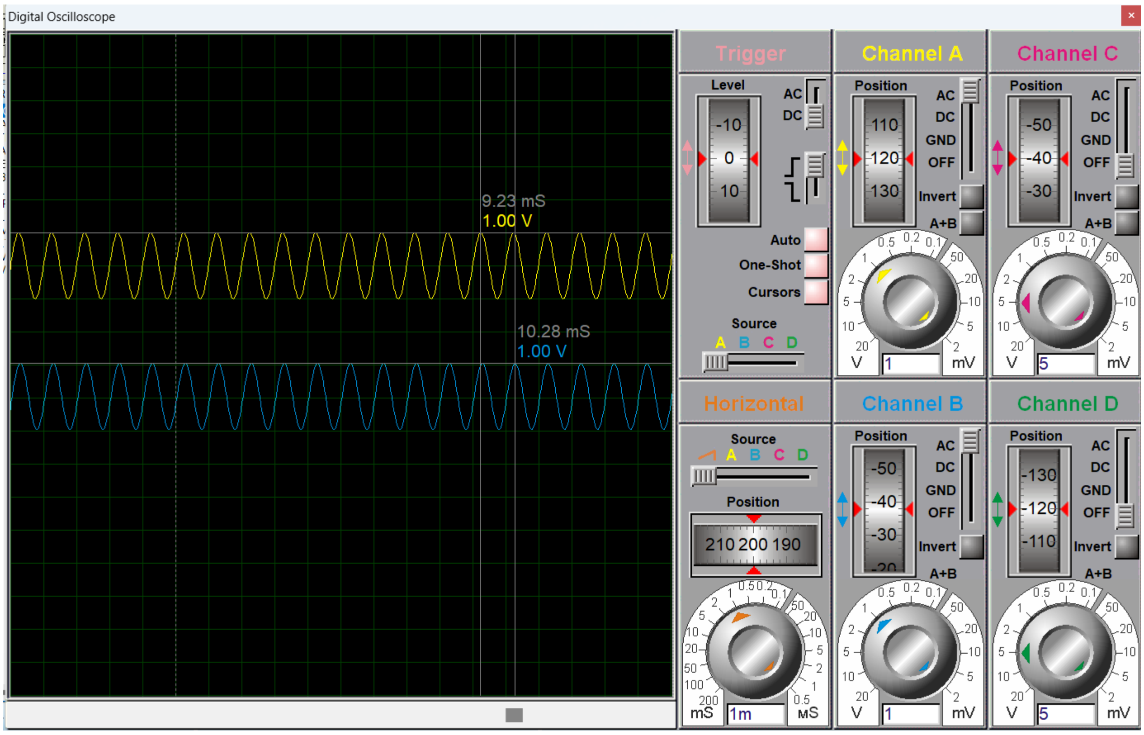

Figure 11 : Simulation result of Proteus

Supplied Voltage : 1 V

Output Voltage : 1 V

4.2 FREQUENCY RESPONSE OF THE FILTER

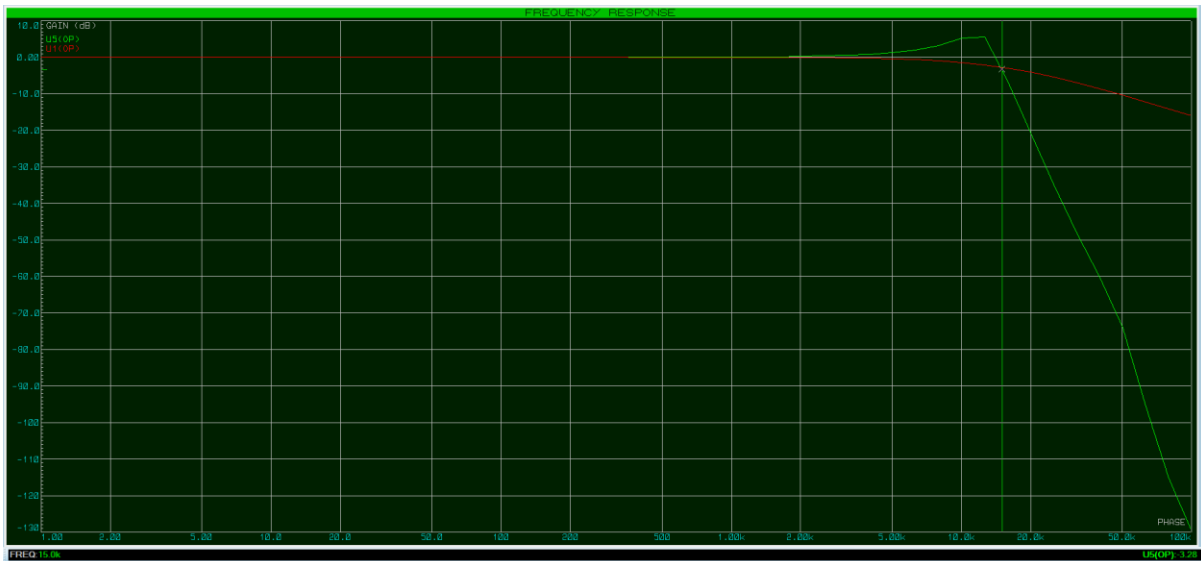

Figure 12 : Frequency response of the filter

Cutoff Frequency = 15 kHz

4.3 PRACTICAL SIMULATION RESULTS

4.4 DISCUSSION

The cutoff frequency of a 9th order Butterworth low pass filter can be practically changed by varying the values of its capacitors and resistors, as well as the properties of the operational amplifier used (in this case, the UA 741 IC). Here are some possible reasons why the cutoff frequency may be changed in practice:

- Component tolerances: Capacitors and resistors have tolerances, which means that their actual values may deviate from their nominal values. This can affect the cutoff frequency of the filter, especially in higher-order filters where the values of multiple components interact. Therefore, careful selection and matching of components with appropriate tolerances is necessary to achieve the desired cutoff frequency.
- Temperature variations: Changes in temperature can affect the values of capacitors and resistors, which can in turn alter the cutoff frequency of the filter. This is particularly relevant for applications that operate over a wide range of temperatures, such as in industrial or automotive settings. Thermal compensation techniques, such as using thermistors or temperature-compensated capacitors, may be employed to mitigate this effect.
- Power supply variations: Variations in the power supply voltage can affect the operating point of the operational amplifier, which can alter the gain and phase response of the filter. This can lead to changes in the cutoff frequency and other filter characteristics. The use of voltage regulators or other power supply conditioning techniques may help to minimize this effect.
- Op-amp characteristics: The UA 741 IC used in the filter has specific input and output impedance, gain-bandwidth product, slew rate, and other performance parameters that affect the behavior of the filter. In particular, the gain-bandwidth product limits the highest frequency at which the amplifier can provide the desired gain, and therefore sets an upper limit on the cutoff frequency of the filter. Other op-amps with different specifications may be used to achieve higher or lower cutoff frequencies, but this may require adjusting the values of the capacitors and resistors in the filter design.

Overall, the cutoff frequency of a 9th order Butterworth low pass filter can be practically changed by modifying its component values and the properties of the operational amplifier used. Careful consideration of component tolerances, temperature and power supply variations, and op-amp characteristics is necessary to achieve the desired filter performance in practical applications.

5 REFERENCES

[1] EE5207 – Electronic Circuit Design Lecture notes

[2] EE4105 – Electronics Project lecture notes.

[3] Jayasundare, Dr. N.D., 2015. Introduction to Electronic Engineering. 1st ed. Colombo.

[4] EE3301 – Analog Electronics lecture notes.

APPENDIX

Butterworth Coefficients

n	i	a_i	b_i	$k_i = f_{Ci} / f_C$	Q_i
1	1	1.0000	0.0000	1.000	—
2	1	1.4142	1.0000	1.000	0.71
3	1	1.0000	0.0000	1.000	—
	2	1.0000	1.0000	1.272	1.00
4	1	1.8478	1.0000	0.719	0.54
	2	0.7654	1.0000	1.390	1.31
5	1	1.0000	0.0000	1.000	—
	2	1.6180	1.0000	0.859	0.62
	3	0.6180	1.0000	1.448	1.62
6	1	1.9319	1.0000	0.676	0.52
	2	1.4142	1.0000	1.000	0.71
	3	0.5176	1.0000	1.479	1.93
7	1	1.0000	0.0000	1.000	—
	2	1.8019	1.0000	0.745	0.55
	3	1.2470	1.0000	1.117	0.80
	4	0.4450	1.0000	1.499	2.25
8	1	1.9616	1.0000	0.661	0.51
	2	1.6629	1.0000	0.829	0.60
	3	1.1111	1.0000	1.206	0.90
	4	0.3902	1.0000	1.512	2.56
9	1	1.0000	0.0000	1.000	—
	2	1.8794	1.0000	0.703	0.53
	3	1.5321	1.0000	0.917	0.65
	4	1.0000	1.0000	1.272	1.00
	5	0.3473	1.0000	1.521	2.88
10	1	1.9754	1.0000	0.655	0.51
	2	1.7820	1.0000	0.756	0.56
	3	1.4142	1.0000	1.000	0.71
	4	0.9080	1.0000	1.322	1.10
	5	0.3129	1.0000	1.527	3.20

Figure 13 : Butterworth Coefficient table

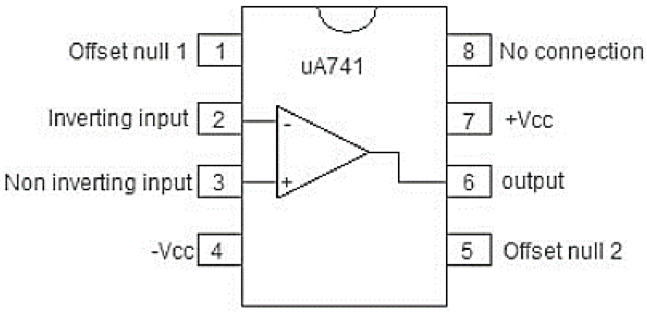

Figure 14 :Pin configuration of UA 741 IC