American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-12, Issue-8, pp-20-25
www.ajer.org
Research Paper Open Access

Development and Characterization of First Order Low-Pass Active Filter

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In electronic systems, the desired signal is much often than not overshadowed by unwanted signals. Attempt to amplify the wanted signals equally amplifies the unwanted one thereby increasing the ratio. Since signals are distinguished by their frequency characteristics, frequency selective circuits (Filters) can be used in filtering the wanted signals from the unwanted signal. Analog filter comes in different forms with different characteristics and can be active or passive. This paper presents the development and characterization of a first order low pass active filter. The active element used here is the Operational Amplifier OP AMP 741. The Transfer Function (TF) equation is derived and characterized with the Band Width (BW), Cut-off Frequency (Fc) and the Quality Factor (Q) specified, derived and actualized. The application of the developed Active Low Pass filter to signal of varied frequencies with fixed input voltage followed with the frequency response plots indicative of the designed specification.

Keywords—*Active filter, Operational Amplifier, Transfer Function, Band Width, Centre frequency, Quality Factor.*

Date of Submission: 24-07-2023 Date of acceptance: 06-08-2023

I. Introduction

The importance of filters in the world of electronics and telecommunication cannot be overemphasized. Filters cut off certain frequencies while enhancing desired frequencies. An electrical filter is a network designed to attenuate certain frequencies but pass others without attenuation [1]. Filters fall under two broad dimensions of Analog and Digital filters. Analog filter classified on their frequency response are Low-pass filter, High-pass filter, Band-pass filter, Band-stop filter and All-pass filter [2]. Analog filters can also be grouped under passive filter and active filters. The advantages of active filters over passive filter include but not limited to the following; absence of insertion loss, easy tuning, no isolation problem due to its high input impedance, pass band gain, flexibility in gain and frequency adjustment, small component size, absence of inductors and relative low cost[3]. Active filter thus gives more efficient, effective, portable and cheaper cost compared to passive filter.

The characteristics and terminologies of a low pass active filter are depicted in figure 1. A Low-Pass Filter(LPF) passes all the frequencies of signal below its cut-off frequency with little or no attenuation and stops all other frequencies which are above the critical frequency *fc.* In LPF, attenuation commences from the cut-off frequency to infinitum. The critical frequency forms the boundary between the two bands known as pass-band and the stop-band of the filter. The pass-band is the range of frequencies which are allowed to pass through to the output by the filter without any attenuation while the stop band is the range of frequencies which are not allowed to pass through to the output by the filter. These are shown in figure 1.

It is pertinent to state that in practice, as opposed to the ideal case, the stop band does not take off immediately from the critical frequency f_c. At *fc*, the gain of the filter is down by 3dB and after *fc*, it reduces at a higher rate[4]. This intermediate band formed between the pass-band and stop-band is known as transition band. The ideal low-pass filter and the practical low-pass filter are shown in figure 2 and 3 respectively

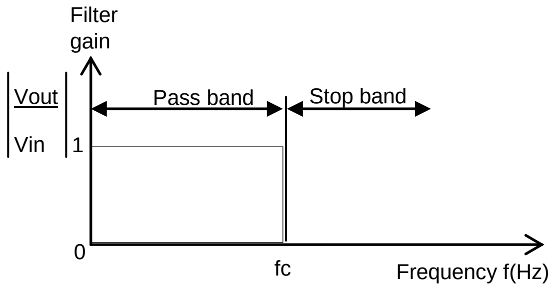
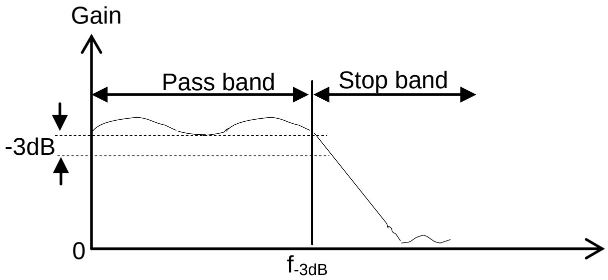
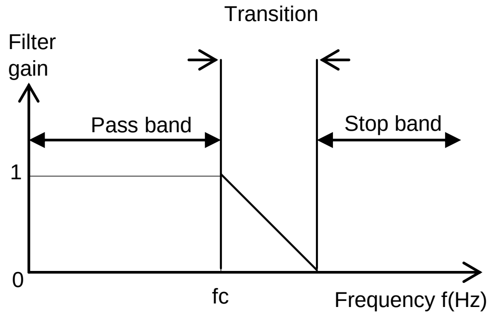


Figure 1: Ideal low-pass filter characteristics



Fiqure 2: Practical low-pass filter characteristics



Fiqure 3: Transition Band

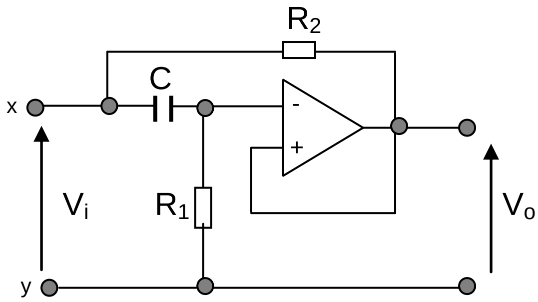
II. MATERIALS AND METHOD

2.1 LC Filter Simulation

An LC filter structure is the starting point in the design of active filters. This is done either by simulating each inductor by a gyro-capacitor combination or by transforming the basic filter structure such that it can be realized with general impedance convectors (GICS) such as Frequency Dependent Negative Resistances (FDNRS)[5]. Both of the above methods of simulation can be realized with the Op-Amps. The circuit on inductance simulation using Op-Amp diagram in figure 4 below can be used for inductance simulation. In this circuit, the value of the inductance is given by the equation 1 below [6].

$$L = \frac{R_2 C (R_1 - R_2)}{1 + W^2 R_2{}^2 C^2} \quad \text{------ 1}$$

By connecting a capacitor across x and y, a tuned circuit is obtained.



Figure

2.2 Transfer Function of first order filter

Transfer function (TF) is a mathematical equation which relates the output to the input signal as a function of the circuit components.[7] This plays an important role in filter design. Active filters are described by their order. This order is determined by the highest power of the polynomial which forms the denominator ie the highest power of S, the Laplace transform operator.

$$s----1^{st}\,order$$

$$s^{2}----=2^{nd}\,order$$

$$s^{n}-------=n^{th}\,order$$

Higher order of filters can be got by cascading of filters. The higher the order, the better is the frequency response characteristics of the filter so formed[8]

2.3 **Realization of First Order Low Pass Active Filter**

Low Pass filter has a constant gain from OHz to a high cut-off frequency Fc. It is pertinent to note that its bandwidth is equal to Fc. At high cut-off frequency, the gain is reduced by 3dB and for any F>Fc, the gain decreases with an increase in frequency. The frequency between 0 to Fc are the pass band frequency while the frequency beyond Fc where attenuation takes place is referred to as the stop band frequencies. An ideal low-pass filter has no loss within the pass band frequencies and an infinite loss at the stop band frequencies. Practically, it is not possible to achieve an ideal low pass filter but with good design techniques, precision components and high speed OP-Amps such as LM318 or ICL 8017, a filter with a good response that approximates to the ideal structure can be achieved. The first order low pass active filter under review is shown in figure 5 below.

Figure5: First order Low Pass Active Filter

From the circuit of figure 5, the filter uses RC network for filtering and the op-amp used in non-inverting mode of configuration.
This is a Butterworth alignment and as such the cut-off frequency is the same as F_3dB

The value of damping factor for the first order low-pass Butterworth filter is always 1.

$Q = 1(\ 1)$

With damping factor = α

$$Q = \frac{1}{\alpha}$$

Resistor R and capacitor C determine the cut-off frequency, while R_1 and R_F determine the gain.
The Op-Amp being used under non-inverting mode configuration, its closed loop $Gain = Amax$

$A_F = 1 + \frac{R_F}{R_1}$ (2)

The pass band gain A_{max} or A_O is also the same with the closed loop gain, so

$Aomax = A_V = A_F (3)$

From figure 5 above,
R and C form a voltage divider network across the input V_{in}

$V_1 = \frac{-j_{xc}}{R - j_{xc}} V_{in}$ (4)

$$but, X_C = \frac{1}{2\pi f_c} V_{in}$$

Substituting for X_C value in equation (4)

$V_1 = \frac{-j\left(\frac{1}{2\pi f_c}\right)}{R - j\left(\frac{1}{2\pi f_c}\right)} V_{in}$ (5)

$V_1 = \frac{V_{in}}{\frac{1 - 2\pi fRC}{j}}$ (6)

Dividing numerator and denominator by –j

$$since \frac{1}{j} = -j, equation(6) becomes$$

$V_1 = \frac{V_{in}}{1 + j2\pi fRC}$ (7)

The filter output voltage Vout is given by;

$V_{out} = A_F x V_1$ (8)

Where A_F = closed loop voltage gain.
Substituting value for A_F and V_1, from equations 2 and 7 respectively, in equation 8 we have;

$V_{out} = \left(1 + \frac{R_F}{R_1}\right) . \left(\frac{V_{in}}{1 + j2\pi fRC}\right)$ (9)

$\frac{V_{out}}{V_{in}} = \frac{A_F}{1 + j2\pi fRC}$ (10)

$since, f_C = \frac{1}{2\pi RC}$ and

$2\pi RC = \frac{1}{f_C}$

$substituting the vaue of\ 2\pi RC in equation (10) yields;$

$\frac{V_{out}}{V_{in}} = \frac{A_F}{1 + j\left(\frac{f}{f_C}\right)}$ (11)

The gain magnitude and phase angle of the low-pass filter can be obtained by converting equation (11) into its equivalent polar form as shown in equation (12) and (13) below

$$\frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_{in}} < 0 \qquad (12)$$

$$\frac{V_{out}}{V_{in}} = \frac{A_F}{\sqrt{1+\left(\frac{f}{fc}\right)^2}} < -tan^{-1}\left(\frac{f}{fc}\right) \qquad (13)$$

Program to run for the gain and network

1. Fix the fc
2. Select C for 0.001 to 0.1µF
3. Calculate value for R using $R = \frac{1}{2\pi f C}$
4. Select values for R_1 and $R_F$as a function of pass band gain. That is;

$$A_F = 1 + \frac{R_F}{R_1}$$

2.3 Circuit Component Realization

The design features leading to component values and other filter characteristics are examined below using the derived transfer function.
The following parameters are used for the filter under development

Cut-off frequency (f_c) = 10kHz resulting in *Wc=62.84k rad/s, Pass band voltage gain =2.5(7.96dB)*
From fig 5 above, the value of R and C are to be calculated having set the cut-off frequency at 10kHz.
Traditionally, C is selected within the range of 0.001 μF to 0.1 μF while R is calculated from the formula in equation 11 below

$$R = \frac{1}{2\pi f_c C} \qquad 10$$

C selected to be 0.0047 μF
Here R = 3.39kΩ

$$\text{Pass band gain } = \left(1 + \frac{R_F}{R_1}\right) \qquad 11$$

Fixing R_F= 10kΩ
From equation 11, R_1 is computed to be 6.6kΩ $\approx 7k\Omega$
OP Amp used is 741

2.4 Organization and Testing

The filter circuit component assembled and in place was subjected to tests to ascertain the performance.With signal generator, a fixed input voltage(Vi) of 1Vp-p with varied frequency from 1kHz to 20kHz was injected to the filter input while the corresponding output voltages were measured. $20\log\frac{V_o}{V_i}$ was computed and tabulated with the other variables; Freq(Hz), Vi, Vo, $\frac{V_o}{V_i}$, $20\log\frac{V_o}{V_i}$ (dB). The frequencyresponse (dB vs Freq) is shown on the graph in figure 6 below.

III. Results and Discussion

The frequency of response plots of the developed first order low filter are shown in figures 6 and 7 below.Figure 6 shows the response of the filter when 1volt peep-peek signal of varied frequencies (1kHz-20kHz)in order of 100Hz increment was used in the testing. The output voltage measured and tabulated. The gain, ratio of the output voltage to the input (Vout/Vinput) plotted against the corresponding frequencies is shownin figure 6.

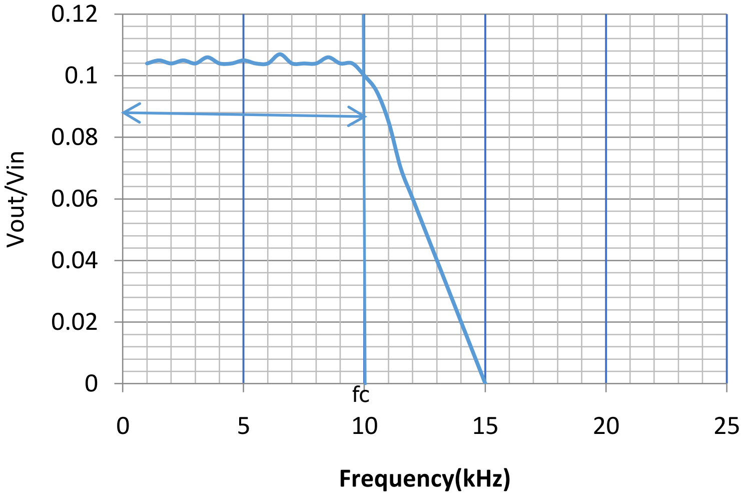


Figure 6: Frequency response of the 1st order low-pass filter

Subsequently, a 20log(Vout/Vinput) in decibel was plotted against their corresponding frequencies and plotted as shown in figure 7 below.

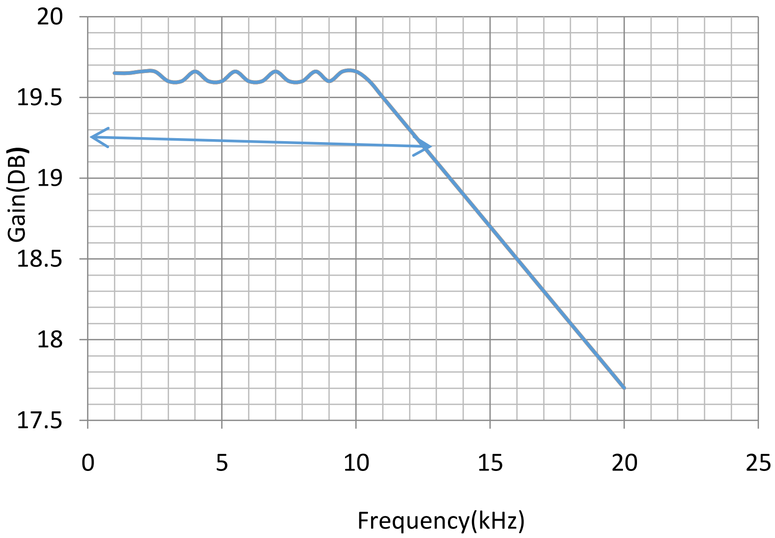


Figure 7: Frequence response of the filter with Gain in dB

IV. Conclusion

The proposed first order low-pass filter has successfully been developed and tested. The frequency response gives a good semblance of first order low-pass filter. This has shown the possibility of simulating inductances or coils out of circuit using active element in operational amplifier when used in its inverting mode. The accuracy becomes a function of choice in the wide range of parameters and the tolerances of the other passive components augmented alongside the active element of the operational amplifier.

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