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Development and characterization of second order Low Pass Active Filter (LPAF)

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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 second 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 and derived. 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, Center frequency, Quality Factor.

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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 below. 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 above.

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 below respectively.

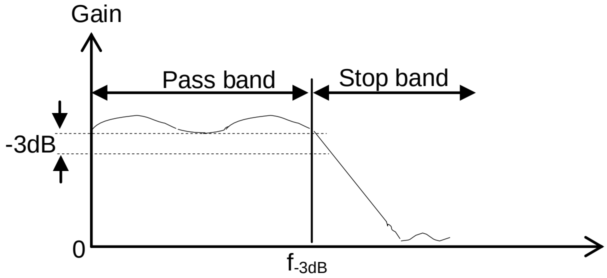

Fig 1: Practical low-pass filter frequency response

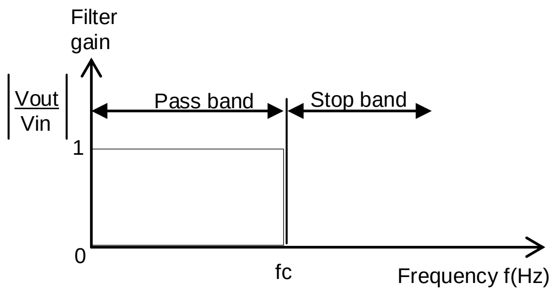

Fig 2: Ideal low-pass filter frequency response

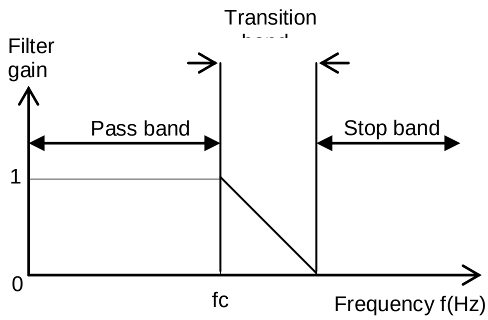

Fig 3: Practical low-pass filter frequency response

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.

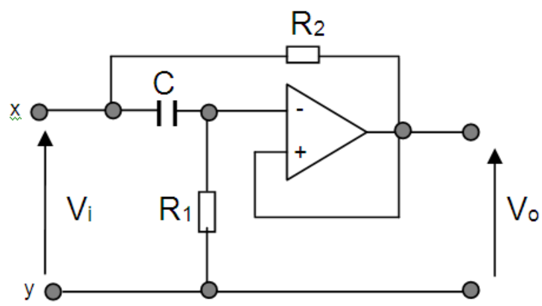

Figure 4: Inductance simulation by Op-Amp

2.2 Transfer Function of second 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] The second order active filter under review is shown in figure 5 below.

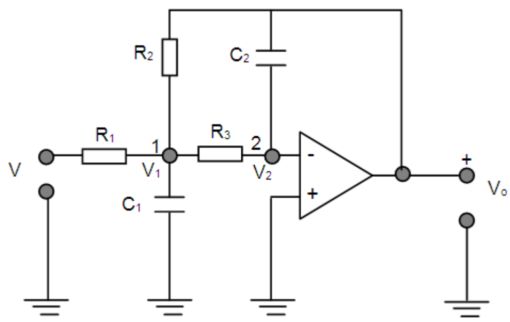

Figure 5: Second order multiple low-pass feedback filter

Analysis:
Node 2 indicated above is at ground potential because the Op-Amp has very high open loop voltage gain A, and takes negligible current. This is the virtual earth concept and will be referred to from time to time throughout the analysis.
Taking Nodal voltage analysis at node 1:

$$\frac{V_1 - V}{R_1} + V_1 SC_1 \left(\frac{V_1 - V_o}{R_2} \right) + \frac{V_1}{R_3} = 0 ------ 2$$

$$\frac{V_1}{R_1} + V_1 SC_1 + \frac{V_1}{R_2} + \frac{V_1}{R_3} = \frac{V}{R_1} + \frac{V_o}{R_2}$$

$$V_1 \left(\frac{1}{R_1} + SC_1 + \frac{1}{R_2} + \frac{1}{R_3} \right) = \frac{V}{R_1} + \frac{V_o}{R_3} ----3$$

At node 2(virtual earth concept)

$$-V_o SC_2 - \frac{V_1}{R_3} = 0$$

$$V_1 = -V_o SC_2 R_3 ------ 4$$

Substituting for the value of V_1 in equation 2 yields

$$-V_o SC_2 R_3 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + SC_1 \right) = \frac{V}{R_1} + \frac{V_o}{R_2}$$

$$-V_o \left(\frac{SC_2 R_3}{R_1} + \frac{SC_2 R_3}{R_2} + SC_2 + S^2 C_1 C_2 R_3 + \frac{1}{r_2} = \frac{V}{R_1} \right) ----4$$

Multiplying equation 4 through by $R_1 R_2$ gives

$$-V_o (SC_2 R_2 R_3 + SC_2 R_3 R_1 + SC_2 R_1 R_2 + S^2 C_1 C_2 R_1 R_2 R_3 + R_1) = VR_2$$

$$\frac{V_o}{V} = \frac{R_2}{S^2 C_1 C \; R_1 R_2 R_3 + S(C_2 R_2 R_3 + C_2 R_2 R_3 + C_2 R_1 R_3 + C_2 R_1 R_2) + R_1}$$

Dividing through by $C_1 C_2 R_1 R_2 R_3$ yields

$$\frac{V_o}{V} = \frac{\frac{1}{C_1 C_2 R_1 R_3}}{S^2 + S\left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_1 R_3} \right) + \frac{1}{C_1 C_2 R_2 R_3}} ----5$$

Equation 5 above is the Transfer Function of the filter

2.3 CIRCUIT COMPONENT REALIZATION

The design features leading to component values and other filter characteristics are examined below using the derived transfer function. A standard transfer function of a second order filter is given in equation 6 below.

$$T.F. = \frac{K}{S^2 + S(BW) + W_o^2} ----6$$

Comparing equation 5 with the standard transfer function of equation 6, it could be deduced that

$$BW = S\left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_1 R_3} \right) ----7$$

$$W_o = \sqrt{\frac{1}{C_1 C_2 R_2 R_3}} ----8 ----8$$

$$K = \frac{1}{C_1 C_2 R_1 R_3} ----9 ----9$$

Where BW = Bandwidth (in radians)
W_o = Centre Frequency (rad/s)
K = Gain constant

The following parameters are used for the filter under development

Bandwidth (BW) = 4kHz
Cut-off frequency (F_c) = 3kHz
Gain at center frequency (β_o) = -4db.

Let

$$\frac{C_1}{C_2} = n$$

$$C_1 = nC_2$$

$$R_1 = R_3 = R$$

and

$$K = \frac{1}{C_1 C_2 R_1 R_3}$$

$$K = \frac{1}{nC_2^2 R^2} ----10$$

$$BW = \frac{1}{nC_2}\left(\frac{2}{R} + \frac{1}{R_2}\right) ----11$$

$$W_O^2 = \frac{1}{nC_2^2 RR_2} ----12$$

From equation 10

$$R^2 = \frac{1}{nC_2^2} K = \frac{1}{C_2\sqrt{nK}} ---13$$

From equation 12

$$R_2 = \frac{1}{nW_o C_2^2 R}$$

$$C_1 = 0.1\mu f\,(0.001\ \mu F - 0.1\mu F)$$

$$C_2 = 20\ nF_o$$

Let $n = \frac{C_1}{C_2} = 5$

$$20 \log \frac{K}{BWS} = -4\,dB$$

(Gain at cut-off frequency)

$S = W_o$ (at cut-off frequency)

$W_o = 18{,}849\ .5559$ rad/sec

$BW = 25{,}132\ .74123$ rad/sec

Hence K=298910370.4

From equation 13,

$= 1.293\ k\Omega \approx 1.3k\Omega$ with $1.2k\Omega$ standard used.

From equation 12,

$R_2 = 1.082\ k\Omega$ with standard $1k\Omega$ used

$R_1 = R_2 = 1.3k\Omega$ with standard $1.2k\Omega$ used

$C_1 = 0.1\mu F$

$C_2 = 20\ nF$

Quality Factor

Quality factor is sometimes referred to as the magnification factor. The higher the Q-factor, the more abrupt the transition phase of the frequency response curve and the narrower the bandwidth [9] The Q-factor gives information on the nature of the filter frequency response curve. This is of much importance in oscillators.

$$Q = \frac{f_o}{f_H - f_L} = \frac{f_o}{BW} ----14$$

$$= \frac{3kHz}{4kHz} = 0.75$$

2.4 ORGANIZATION AND TESETING

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 .8kHz to 2.2kHz 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 frequency response (dB vs Freq) is shown on the graph in figure 6 below.

III. RESULTS AND DISCUSSION

The frequency of response plots of the developed second order 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 (0-5kHz) in order of 200Hz increment was used in the testing. The output voltage measured and tabulated. The gain, ratio of output voltage to the input (Vout/Vinput) plotted against the corresponding frequencies plotted is shown in figure 6.

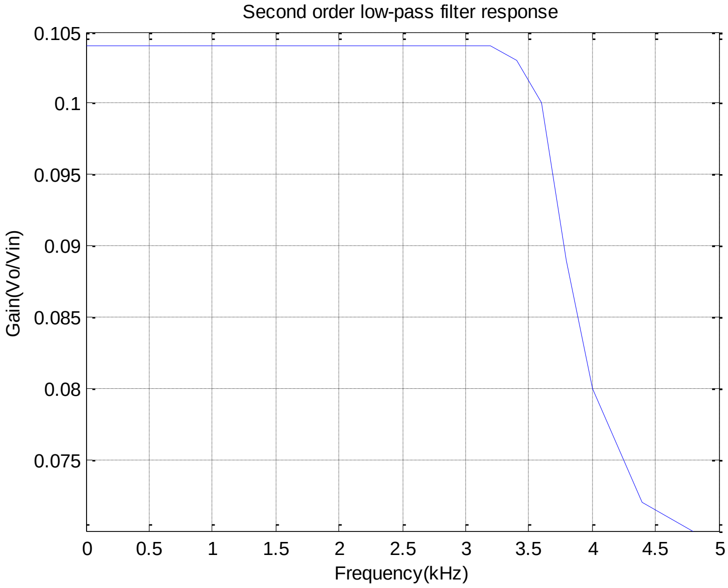

Figure 6: Frequency response of the 2nd order low-pass filter

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

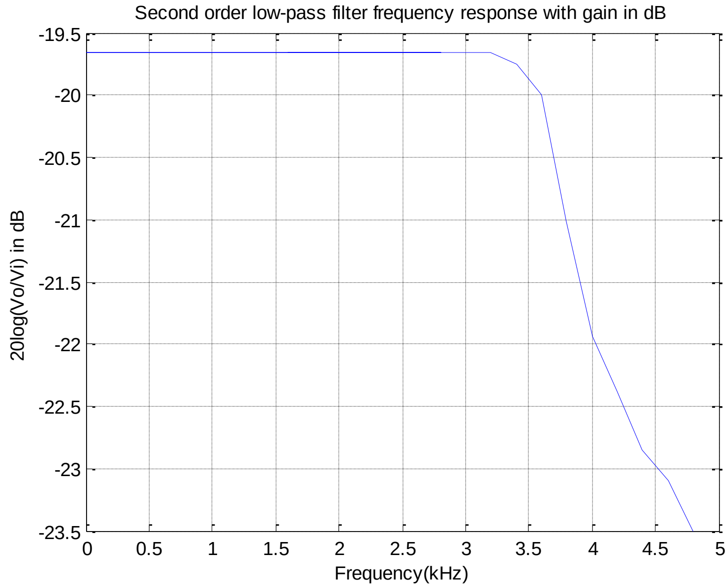

Figure 7: Freq response of filter with Gain in dB

IV. CONCLUSION

The proposed second order low-pass filter has successfully been developed and tested. The frequency response gives a good semblance of second 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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