EXPERIMENT 2: APPLICATION OF AN OPAMP BASED ACTIVE FILTER

List Of Components:

Opamp: 2 x LM324 or 4 x LM741
Resistors: 2 x 15 kΩ, 2 x 7.5 kΩ
Capacitors: 2 x 10 nF, 2 x 4.7 nF

Objective: To design a first order lowpass, a first order highpass and a second order bandpass filter by using active devices.

2.1. General Information:

Filters are the most basic analog circuits. Filters are used to shape frequency spectrums of electrical signals. Only passive (R, L and C components) or only active devices (op-amp, transistor etc.) can be used to realize filters. It can be also a combination of active and passive devices.

Filters are widely used in electronics and telecommunication systems. The objective is to select the desired frequency range of a signal. Depending on the transfer function, it can be a low-pass, a high-pass, a band-pass or a band-stop filter. The Cut-off frequency, the quality factor and the pass-band gain are some of the important parameters of a filter.

Resistors, coils and capacitors are used in passive filters. The roots of the transfer function are real numbers in RC filters. They have low quality factors. In order to obtain higher quality factor, one should use LC filters. On the other hand, the required coil inductance is too high at low frequency range and therefore such a circuitry requires a bigger space which in turn increases the cost. Hence, active filters are preferred at low frequency range.

The biggest advantage of active filters is their small size and low weight. They are more reliable, cost-effective (because of the mass production) and they have lower parasitic impedance due to their smaller size. None the less, their pole frequencies are limited by the bandwidth of the utilized active components. Moreover, pole frequency and quality factor, which indicates the sharpness of the filter, are inversely proportional. Therefore, an optimum solution has to be found. Besides, active filter characteristics are strongly depended on the variations of the components and they required extra power supplies for the active devices that are used.

2.1.1. Determination of the Filter Type

One can determine the filter type by taking the limits of the functions that are seen below for \( s \to 0 \) and \( s \to \infty \). Let’s examine the transfer function of a low-pass filter (LPF).

\[
\lim_{s \to 0} H_{LPF}(s) = \lim_{s \to 0} \frac{K}{s + w_c} = \frac{K}{0 + w_c} = A
\]  

(2.1)
\[
\lim_{s \to \infty} H_{LPF}(s) = \lim_{s \to 0^+} \frac{K}{s + w_c} = \frac{K}{\infty + w_c} = 0
\]
(2.3)

A is the maximum gain of the filter. As it can be seen in the equations above, the gain of the filter at high frequency range is equal to zero and it approaches to the maximum gain at low frequency. The other filters can be analyzed by examining their transfer function.

2.1.2. Filter Characteristics

2.1.2.a) Low Pass Filter

It has a constant gain (mostly unity) between 0 Hz and cut-off frequency \(f_H\) in a LPF. At cut-off point, the gain decreases 3 dB. Between 0 Hz and cut-off frequency \(f_H\) is called pass band and beyond \(f_H\) is called stop band. Gain is very low at the stop band.

2.1.2.b) High Pass Filter

It has a constant gain (mostly unity) over \(f_L\). Gain is reduced by 3 dB at cut off frequency compared to high frequency gain. Between 0 Hz and cut-off frequency \(f_L\) is called stop band and below \(f_L\) is called pass band. Gain is very low at the stop band. Gain is very low at the stop band.
2.1.2.c) Band-Pass Filter

Band pass filter (BPF) passes the desired frequency range and attenuates the rest of the spectrum. Pass band lies between two cut-off frequencies \( f_L \) and \( f_H \). Band width is expressed as \( B = f_H - f_L \).

\[
H_{\text{LPF}}(s) = \frac{K}{s + w_c}
\]  

2.1.3. Filter Transfer Functions and Circuit Analysis

2.1.3.a) First Order Low Pass Filter: The transfer function of a first order low pass filter is given below.

\[
H_{\text{LPF}}(s) = \frac{K}{s + w_c}
\]  

Figure 2.2. HPF characteristics (a) Ideal (b) Actual

Figure 2.3. BPF characteristics (a) Ideal (b) Actual
K is the gain and \( w_c \) is the cut-off frequency in this formula. The analysis of the circuit given in Figure 2.4 is done and shown in Equation 2.5.

\[
\frac{V_o}{V_i}(s) = \frac{1}{R_s C} \left( s + \frac{R_s C}{R_i C} \right)
\]

(2.5)

\[ K = \frac{1}{R_i C} \quad \text{and} \quad w_c = \frac{1}{R_i C} . \]

2.1.3.b) First Order High Pass Filter: The transfer function of a first order high pass filter is given below.

\[
H_{HPF}(s) = \frac{K \cdot s}{s + w_c}
\]

(2.6)

K is the gain and \( w_c \) is the cut-off frequency in this formula. The analysis of the circuit given in Figure 2.5 is done and shown in Equation 2.7.
\[ \frac{V_o}{V_i} (s) = -\frac{R_1}{R_2} \cdot \frac{s}{s + \frac{1}{R_2C}} \] (2.7)

\[ K = \frac{R_1}{R_2} \text{ and } w_c = \frac{1}{R_2C}. \]

2.1.3.b) Second Order Band Pass Filter: The transfer function of a second order band pass filter is given below.

\[ H_{bpf} (s) = \frac{K \cdot \beta s}{s^2 + \beta s + w_0^2} \] (2.8)

K is the gain, \( \beta \) is the band width and \( w_0 \) is the central frequency in this formula. Band width is expressed as \( \beta = w_0/Q \). \( Q \) is called as quality factor. As the quality factor increases, band width is reduced and the gain is enhanced.

![Band Pass Filter Diagram](image)

**Figure 2.6.** Band Pass Filter

\[ \frac{V_o}{V_i} (s) = -\frac{s/R_2C_1}{s^2 + s \left( \frac{1}{R_2C_2} + \frac{1}{R_1C} \right) + \frac{1}{R_1C_1R_2C_2}} \] (2.9)

Central frequency and band width can be written as follows:

\[ f_0 = \frac{1}{2\pi \sqrt{R_1C_1R_2C_2}} \] (2.10)

\[ \beta = \frac{1}{2\pi} \left( \frac{1}{R_1C_1} + \frac{1}{R_2C_2} \right) \] (2.11)
2.1.4 Filter Design Criteria:

2.1.4.a) Band-pass Gain

It is possible to get higher gain than unity in active filters. Many active filters have gain coefficient which determines the gain of the filter. Filters which has flat band gain are widely used. Such filters are called as Butterworth filters. The other class of filters, Chebyshev Filters, have ripples at the pass band gain.

![Butterworth versus Chebyshev](image)

**Figure 2.7.** Butterworth versus Chebyshev

2.1.4. b) Cut-off frequency:

Cut off frequencies $f_H$ and $f_L$ are determined by the components in the filter circuit.

2.1.4. c) Roll-off Rate

Roll-off rate is a term commonly used to describe the steepness of a transmission function with frequency. High roll off rate is desired. As seen in Figure 2.7, it is higher in Chebyshev filter than that of Butterworth filter. The slop of the gain is determined by the quality factor. For example if a first order filter has a slope of 20 dB/decade, a second order filter would have 40 dB/decade slope.

2.1.4. d) Quality Factor:

Quality factor ($Q$) for a band pass filter depends on the central frequency ($f_0$) and the band width ($\beta$).
\[ Q = \frac{f_0}{\beta} \]  

(2.12)

Q is defined as the pole quality for low-pass and high-pass filters. It is distance between 0 dB line and peak of the gain response. It can be 1 the lowest.

### 2.2. Preliminary Studies

1. Study the LM741 datasheet.
2. Simulate the circuits shown in Figure 2.8 and 2.9 by SPICE program as described below:
   a) Make AC analysis of the circuit and find the cut-off frequencies, maximum output amplitude, central frequency, band width and maximum output amplitude of the band pass filter.

### 2.3. Experiment

#### 1- Low pass Filter:

1. Set up the first circuit shown in Figure 2.8.
2. Apply \( V_{ip-p} = 20 \) mV. Supply voltages for the opamps are +/- 12 V.
3. Find the cut-off frequency. Adjust the input frequency as listed in the table. Fill in Table 2.1 according to what you observe at the oscilloscope.
4. By using your findings, draw the gain-frequency graphic. (Figure 2.10)

#### 2- High pass Filter:

1. Set up the second circuit shown in Figure 2.8.
2. Apply \( V_{ip-p} = 20 \) mV. Supply voltages for the opamps are +/- 12 V.
3. Find the cut-off frequency. Adjust the input frequency as listed in the table. Fill in Table 2.2 according to what you observe at the oscilloscope.
4. By using your findings, draw the gain-frequency graphic. (Figure 2.11)

#### 3- Band pass Filter:

1. Set up the circuit shown in Figure 2.9.
2. Apply \( V_{ip-p} = 20 \) mV. Supply voltages for the opamps are +/- 12 V.
3. Find the central and low and high cut-off frequencies. Adjust the input frequency as listed in the table. Fill in Table 2.3 according to what you observe at the oscilloscope.
4. By using your findings, draw the gain-frequency graphic. (Figure 2.12)
2.4. Questions

1. Compare the active and passive filters; list the advantages and disadvantages of both design approaches.

2. What are the properties of coils. What are the advantages and disadvantages of using a coil in a circuit?

3. What are the application areas of low pass filters?

4. What are the application areas of band pass filters?

5. What are the application areas of band stop filters?

6. How can we connect low order filters to each other in order to get high order filters?

7. How can we get a band pass filter using low pass filters?

8. What is the input and output impedances of an ideal Opamp?

9. Design an integrator and a differentiator circuit by using Opamps. Define their transfer functions.
2.5. EXPERIMENT 2 RESULTS PAGE

Table 2.1 The measured gain values at certain frequencies for the Low Pass Filter

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Vo p-p</th>
<th>Av</th>
<th>Av (dB)</th>
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<tr>
<td>0.5(f_c)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.8(f_c)</td>
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<td>(f_c)</td>
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<td>1.5(f_c)</td>
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<tr>
<td>3(f_c)</td>
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</tbody>
</table>

Figure 2.10 Gain – Frequency Characteristics of the Low Pass Filter

Table 2.2 The measured gain values at certain frequencies for the High Pass Filter

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Vo p-p</th>
<th>Av</th>
<th>Av (dB)</th>
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<tr>
<td>0.5(f_c)</td>
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<td>0.8(f_c)</td>
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<td>1.5(f_c)</td>
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<td>3(f_c)</td>
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</table>
Figure 2.11 Gain – Frequency Characteristics of the High Pass Filter

Table 2.3 The measured gain values at certain frequencies for the Band Pass Filter

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Vo p-p</th>
<th>Av</th>
<th>Av (dB)</th>
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Figure 2.12 Gain – Frequency Characteristics of the Band Pass Filter