Sallen-Key High Pass Filter

Objectives:
After performing this lab exercise, learner will be able to:

- Understand & analyze working of Sallen-Key topology of active filters
- Design & build a Sallen-Key high pass filter using opamp
- Establish relationship between input and output signal - prepare a Bode plot for the filter circuit
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:
To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
  - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
  - Resistor (2 x 1K ohms)
  - Capacitor (2 x 0.1 uF)
- BNC cables
- Breadboard and connecting wires
Theory / Key Concepts:
Before performing this lab experiment, it is important to learn following concepts:

- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- A high-pass filter is an electronic circuit that attenuates signals with a frequency lower than a certain value and passes signals of higher frequencies.
  - The 'certain' frequency after which the attenuation ends is called as 'cut-off frequency' of the filter.
  - Range of frequencies below cut-off frequency is called stop band and higher frequency ranges are called pass band.
- At cut-off frequency, the signal amplitude is 0.707 times of its value in the passband i.e., the signal level is 3dB below the passband value.
- Professors R.P. Sallen and E.L. Key described a new filter topology in 1955, which was named after them, the Sallen-Key filters.
- An active Sallen-Key filter can be cascaded easily to make higher order filters. The opamp provides the buffering between cascaded stages.
- Sallen-Key filter gives the flexibility of modifying the filter characteristics (cut-off frequency and Q) using R, C values and amplifier gain. This makes filter design easy.

Circuit Design:
Learner can use the theoretical design rules to calculate the circuit component values:

- A generic Sallen-Key high pass filter circuit is shown below with filter parameters:
Where:

- $K = \text{amplifier gain} = 1 + (R_4 / R_3)$
- Transfer function $= \frac{V_0}{V_i}$

$$
\frac{K(s^2R_1R_2C_1C_2)}{s^2(R_1R_2C_1C_2) + s(2R_2C_2 + R_2C_1 + R_1C_2(1 - K)) + 1}
$$

- Cut-off frequency $= \frac{1}{2\pi \sqrt{R_1R_2C_1C_2}}$

and

$$
Q = \frac{\sqrt{R_1R_2C_1C_2}}{R_2C_2 + R_2C_1 + R_1C_2(1 - K)}
$$

- We can simplify the filter design by choosing $R_1 = R_2 = R = 1k\ \text{Ohms}$ and $C_1 = C_2 = C = 0.1\mu\text{F}$. The opamp gain is kept unity ($R_4 = 0$ and $R_3 = \text{infinty}$).

- This makes
  - Amplifier gain $K = 1$
With the given R and C values, the cut-off frequency will be 1592 Hz, Q = 1/2 and K (opamp amplifier gain) = 1

**Sallen-Key_High_Pass_Filter -- Procedures**

**Step 1**

**Check Your Understanding:**

Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

- What will be the slope of magnitude response in the stop band of a Sallen-Key high-pass filter?
  - -20dB / decade
  - 0 dB / decade
  - -40dB / decade
  - +20dB / decade

- How will the phase response for Sallen-Key high-pass filter vary with frequency of input signal?
  - Phase will vary from 0 to 90 degrees as frequency goes low to high
  - Phase will vary from 0 to -90 degrees as frequency goes low to high
  - Phase will vary from 0 to -180 degrees as frequency goes low to high
  - Phase will vary from 180 to 0 degrees as frequency goes low to high

- The response of the filter circuit will produce any overshoot or oscillation for:
  - Q > 0.5
  - Q = 0.5
  - Q < 0.5
  - Q = infinity

**Step 2**

**Circuit diagram / Connection Details**

- Using the jumper / connecting wires prepare the circuit as shown below - Choose C1 = C2 = 0.1uF & R1 = R2 = 1k ohm.
- When using the ASLK board, you will have to use additional R and C (not available on board) on the small breadboard provided
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -

- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
  - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point
• Use signal from AFG/signal generator to feed to opamp input
• Probe at input and output pins of the filter to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

Make the Circuit Work

• Use signal from AFG/signal generator to feed to opamp input
• Set sinusoidal signal from channel 1 of the AFG
  • amplitude = 1 V_{pp}
  • frequency = 10K Hz
• Autoset the oscilloscope to see both input and output waveforms

Step 5

Taking the Measurements

• Set input
  • Sinusoidal, 1V peak-to-peak amplitude
  • 100 Hz frequency
  • Continuous mode (on AFG)
  • enable the channel 1 output on AFG

• Autoset the oscilloscope to optimally see both input and output signal
• Set up following measurements:
  • On Ch1 - V_{pp}, V_{rms}, Frequency
  • On Ch2 - V_{pp}, V_{rms}, and Phase (between Ch1 and Ch2)
• Keeping the amplitude of the sinusoid input fixed at 1V peak-to-peak, vary its frequency from 100Hz to 100kHz. You may take more readings near cut-off frequency.
• Tabulate the measurements. You can also capture screenshot for each measurement set.

![Amplitude-Frequency Graph](image)

**Step 6**

**Analyzing the Result**

• The observation table would look like as shown below. Calculate voltage gain (observed from measurements) and its decible equivalent.

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<thead>
<tr>
<th>#</th>
<th>Frequency (Hz)</th>
<th>Vpp (V)</th>
<th>Vrms (mV)</th>
<th>Vpp (V)</th>
<th>Vrms (mV)</th>
<th>Phase Difference (Degrees)</th>
<th>Voltage Gain</th>
<th>Voltage Gain (dB)</th>
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• Prepare Bode plot - plot voltage gain and phase against frequency.
Find out the cut-off frequency from the plot (where the gain drops to -3dB from its passband value)

**Step 7**

**Conclusion**

The analysis of the observed results confirm that (As expected):

- The voltage gain of the filter circuit increases to 1 (0 dB) as input frequency is increased
- The attenuation roll-off is -40dB/decade as it is a 2\textsuperscript{nd} order filter
- The cut-off frequency (where gain is -3dB or 3dB down from its passband value) is 2800Hz.
- At the estimated (calculated from R and C values) cut-off frequency of 1592 Hz, the gain is down by ~ 6dB and phase is -90 degrees. (Positive sign in the phase signifies, output leads input)