Sallen-Key_Low_Pass_Filter -- Overview

Mukesh Soni
Researcher / PhD Student
Mechanical Engineering Department
The University of Melbourne

Sallen-Key Low 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 low 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:

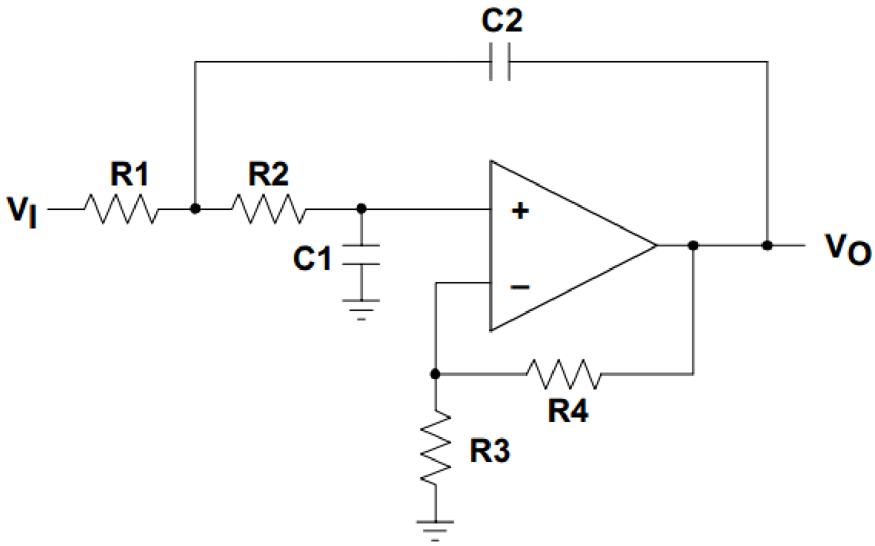
Before performing this lab experiment, it is important to learn following concepts:

- 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 low pass filter is an electronic circuit that passes signals with a frequency lower than a certain value and attenuates signals of higher frequencies.
  - The 'certain' frequency after which the atteneuation starts is called as 'cut-off frequency' of the filter.
  - Range of frequencies below cut-off frequency is called pass-band and higher frequency ranges are called stop 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 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.
- Low pass filter is used for eliminating high-frequency noise from the system.

Circuit Design:

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

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



Where:

- K = amplifier gain = 1 + (R4 / R3)
- Transfer function = V_0/V_i

$$= \frac{K}{s^2(R1R2C1C2) + s(R1C1 + R2C1 + R1C2(1 - K)) + 1}$$

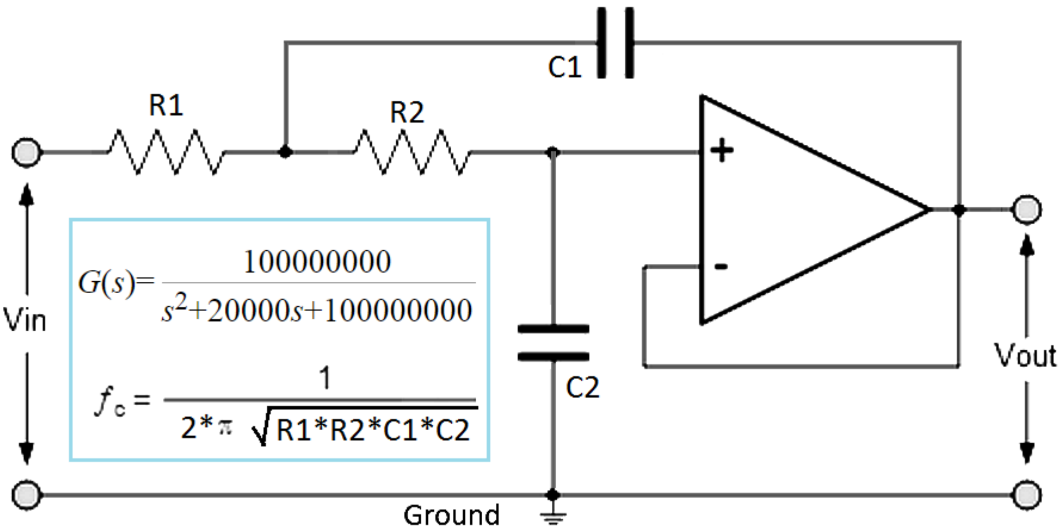
- Cut-off frequency =

$$fc = \frac{1}{2\pi\sqrt{R1R2C1C2}}$$

and

$$Q = \frac{\sqrt{R1R2C1C2}}{R1C1 + R2C1 + R1C2(1 - K)}$$

- We can simplify the filter design by choosing R1 = R2 = R = 1k Ohms and C1 = C2 = C = 0.1uF. The opamp gain is kept unity (R4 = 0 and R3 = 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_Low_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 low-pass filter?
  - -20dB / decade
  - 0 dB / decade
  - -40dB / decade
  - +20dB / decade

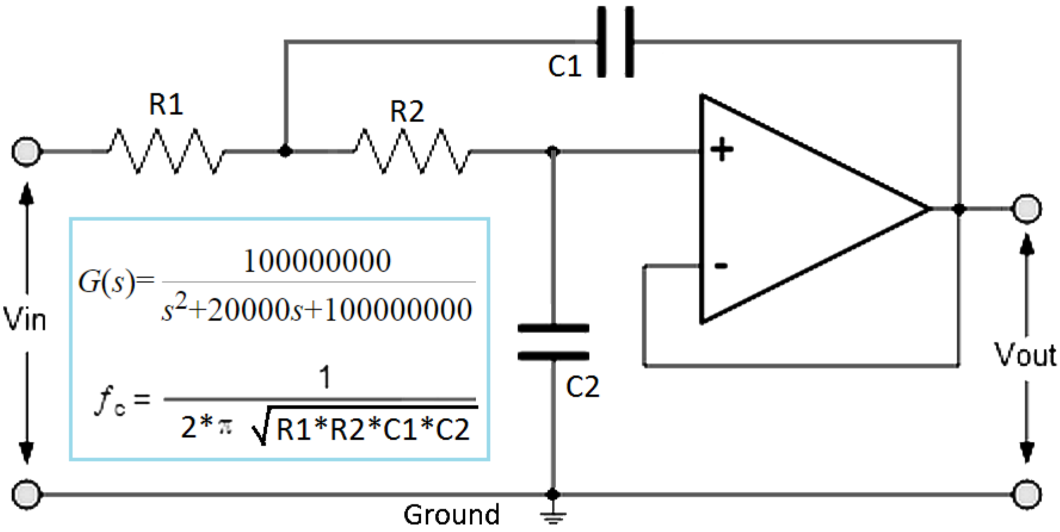
- How will the phase respones for Sallen-Key low pass filter vary with frequency of input signal?
  - Phase will vary from 0 to 90 degrees as frequency goes low to high
  - Phase will vary from 0 to -90 degrees as frequency goes low to high
  - Phase will vary from 0 to -180 degrees as frequency goes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

- The response of the filter circuit will not produce any overshoot or oscillation for:
  - Q = 1
  - Q = 0.5
  - Q < 0.5
  - Q = infinity

Step 2

Circuit diagram / Connection Details

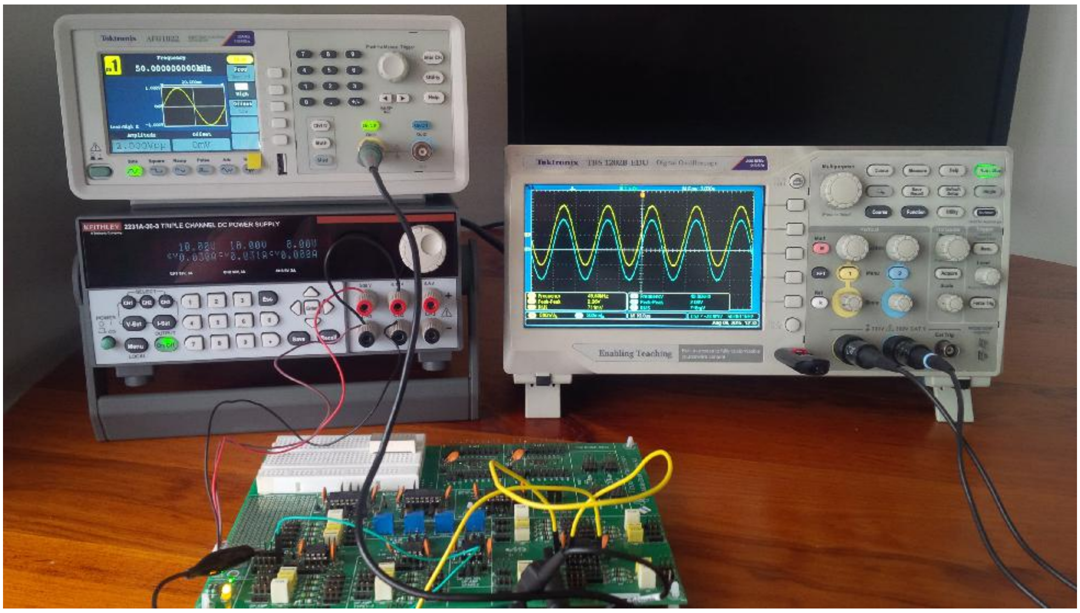
- Using the jumper / connecting wires prepare the circuit as shown below - Choose C1 = C2 = 0.1uF & R1 = R2 = 1k ohm.
- When using the ASLK board, you will have to use additional R and C (not available on board) on the small breadboard provided



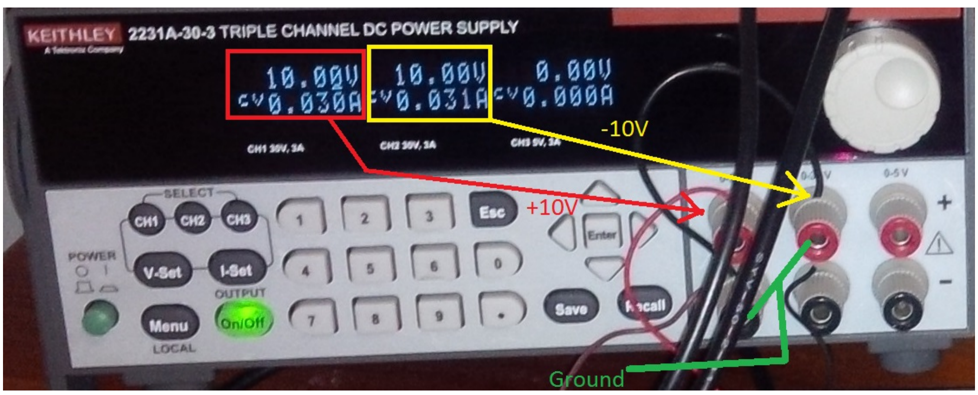
Step 3

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

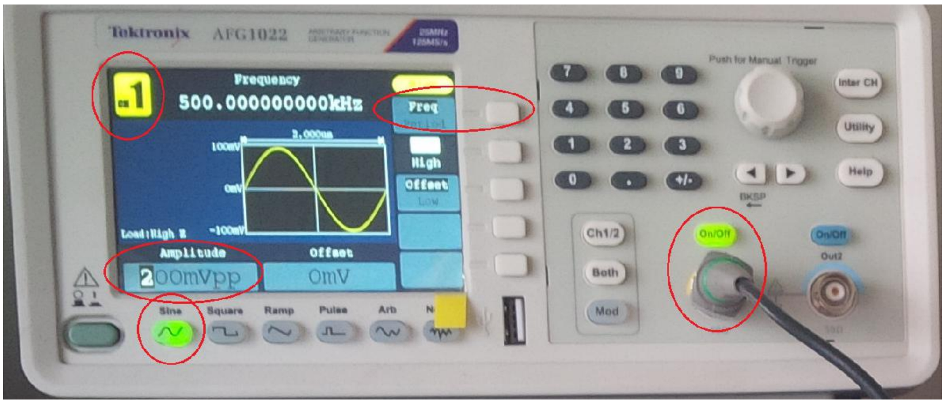
Make the Circuit Work

- 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 = 50 Hz
- Autoset the oscilloscope to see both input and output waveforms

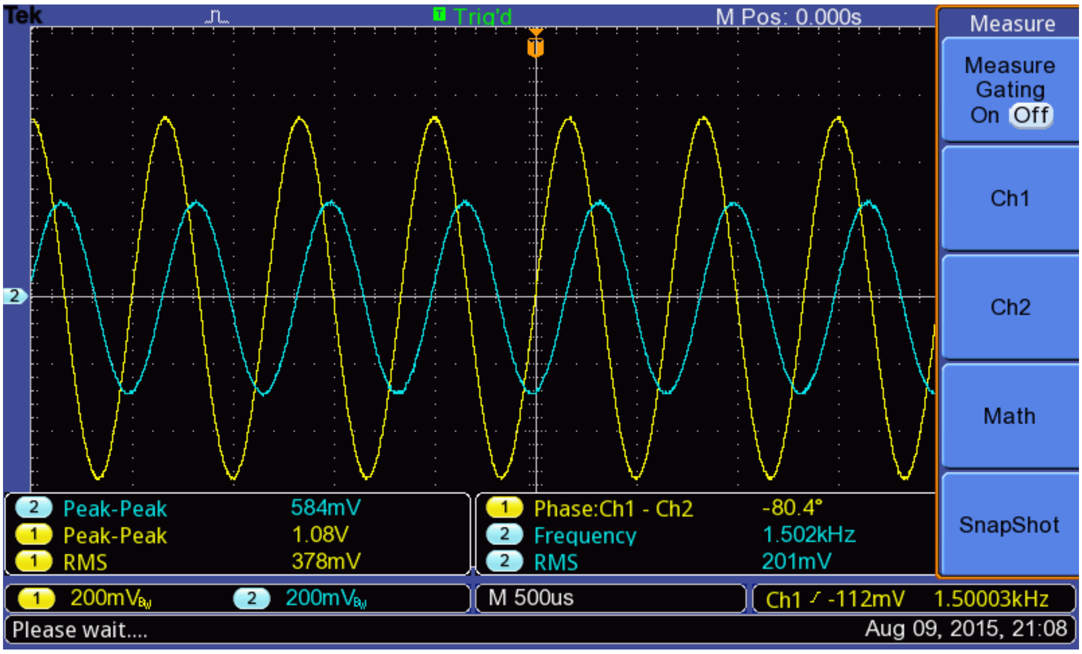
Step 5

Taking the Measurements

- Set input
  - Sinusoidal, 1V peak-to-peak amplitude
  - 1 Hz frequency
  - Continous 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 1Hz to 50kHz. You may take more readings near cut-off frequency.
- Tabulate the measurements. You can also capture screenshot for each measurement set.



Step 6

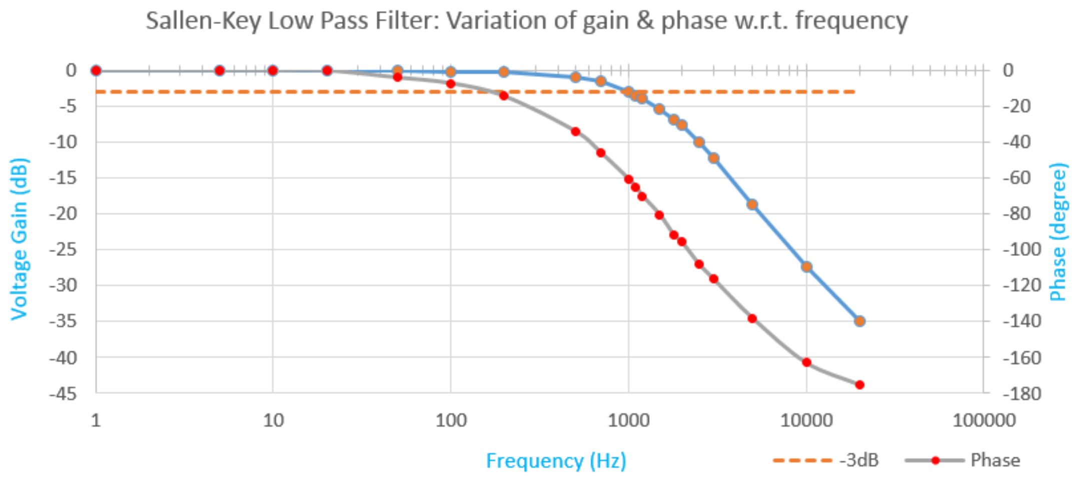
Analyzing the Result

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

#	Frequency (Hz)	INPUT		OUTPUT		Phase Difference (Degrees)	Voltage Gain	Voltage Gain (dB)
		Vpp (V)	Vrms (mV)	Vpp (V)	Vrms (mV)			
1	1	1.030	358	1.03	357.0	0.00	1.00	0.00
2	5	1.030	358	1.02	356.0	0.00	0.99	-0.08
3	10	1.030	358	1.02	356.0	-0.07	0.99	-0.08
4	20	1.030	358	1.02	356.0	-0.08	0.99	-0.08
5	50	1.030	358	1.020	356.0	-3.97	0.99	-0.08
6	100	1.030	358	1.010	354.0	-7.20	0.98	-0.17
7	200	1.030	358	1.000	350.0	-14.40	0.97	-0.26
8	500	1.030	358	0.920	324.0	-33.80	0.89	-0.98
9	700	1.030	358	0.872	301.0	-45.90	0.85	-1.45
10	1,000	1.050	368	0.752	261.0	-60.40	0.72	-2.90
11	1,100	1.060	370	0.712	248.0	-64.80	0.67	-3.46
12	1,200	1.060	372	0.680	235.0	-69.90	0.64	-3.86
13	1,500	1.080	378	0.584	201.0	-80.40	0.54	-5.34
14	1,800	1.100	384	0.496	172.0	-91.60	0.45	-6.92
15	2,000	1.100	388	0.456	156.0	-95.70	0.41	-7.65
16	2,500	1.130	396	0.360	121.0	-108.00	0.32	-9.94
17	3,000	1.150	402	0.280	96.7	-116.00	0.24	-12.27
18	5,000	1.190	413	0.138	44.0	-138.00	0.12	-18.71
19	10,000	1.210	420	0.052	13.1	-162.70	0.04	-27.34
20	20,000	1.220	422	0.022	4.4	-175.00	0.02	-34.88

** MINUS sign in the phase signifies that output lags input

- 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 reduces as input frequency is increased
- The roll-off is -40dB/decade as it is a 2^{nd} order filter
- The cut-off frequency (where gain is -3dB or 3dB down from its passband value) is 1000Hz.
- 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. (minus sign in the phase signifies, output lags input)