Analog Engineer's Circuit

Single-supply, 2nd-order, Sallen-Key high-pass filter circuit

Amplifiers

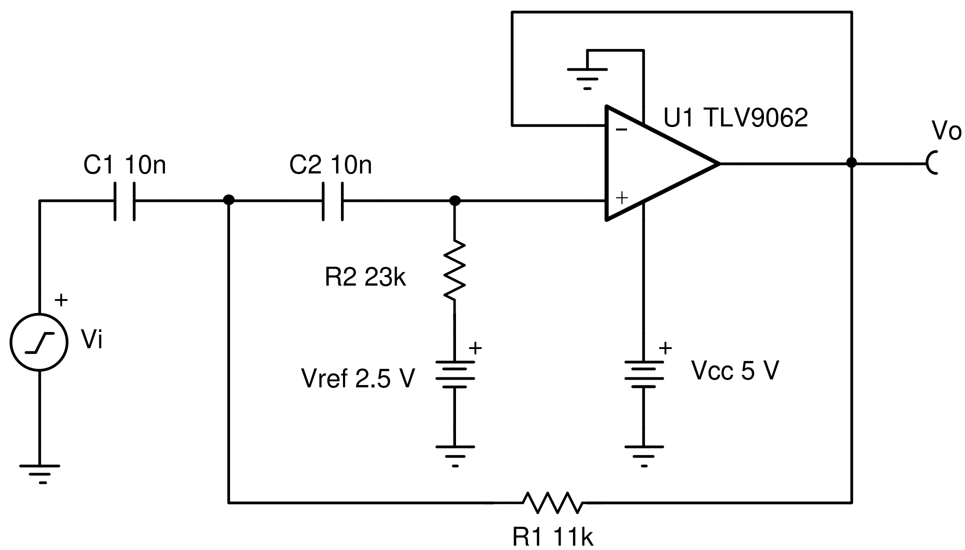
Input		Output		Supply	
V_{iMin}	V_{iMax}	V_{oMin}	V_{oMax}	V_{cc}	V_{ee}
–2.45V	+2.45V	0.05V	4.95V	5V	0V

Gain	Cutoff Frequency (f_c)	Max Frequency (f_{max})	V_{ref}
1V/V	1kHz	10kHz	2.5V

Design Description

The Butterworth Sallen-Key (SK) high-pass (HP) filter is a 2nd-order active filter. Vref provides a DC offset to accommodate for single-supply applications.

An SK filter is usually preferred when small Q factor is desired, noise rejection is prioritized, and when a non-inverting gain of the filter stage is required. The Butterworth topology provides a maximally flat gain in the pass band.



Design Notes

1. Select an op amp with sufficient input common-mode range and output voltage swing.
2. Add V_{ref} to bias the input signal to meet the input common-mode range and output voltage swing.
3. Select the capacitor values first since standard capacitor values are more coarsely subdivided than the resistor values. Use high-precision, low-drift capacitor values to avoid errors in f_c.
4. To minimize the amount of slew-induced distortion, select an op amp with sufficient slew rate (SR).
5. For HP filters, the maximum frequency is set by the gain bandwidth (GBW) of the op amp. Therefore, be sure to select an op amp with sufficient GBW.

Design Steps

The first step is to find component values for the normalized cutoff frequency of 1 radian/second. In the second step the cutoff frequency is scaled to the desired cutoff frequency with scaled component values.

The transfer function for the second-order Sallen-Key high-pass filter is given by:

$$H(s) = \frac{s^2}{s^2 + s\left(\frac{1}{R_2 \times C_1} + \frac{1}{R_2 \times C_2}\right) + \frac{1}{R_1 \times R_2 \times C_1 \times C_2}}$$

$$H(s) = \frac{s^2}{s^2 + a_1 \times s + a_0}$$

where,

$$a_1 = \frac{1}{R_2 \times C_1} + \frac{1}{R_2 \times C_2},\ a_0 = \frac{1}{R_1 \times R_2 \times C_1 \times C_2}$$

1. Set normalized values of C_1 and C_2 (C_{1n} and C_{2n}) and calculate normalized values of R_1 and R_2 (R_{1n} and R_{2n}) by setting w_c to 1 radian/sec (or fc = 1 / (2 × π) Hz). For the second-order Butterworth filter, (see the *Butterworth Filter Table* in the *Active Low-Pass Filter Design Application Report*).

   $$a_0 = 1,\ a_1 = \sqrt{2},\ \text{let } C_{1n} = C_{2n} = 1\text{ F, then } R_{1n} \times R_{2n} = 1 \text{ or } R_{2n} = \frac{1}{R_{1n}},\ \ a_1 = \frac{2}{R_{2n}} = \sqrt{2}$$

   $$\therefore R_{2n} = \sqrt{2} = 1.414\Omega\ ,\ R_{1n} = \frac{1}{R_{2n}} = 0.707\Omega$$

2. Scale the component values and cutoff frequency. The resistor values are very small and capacitors values are unrealistic, hence these have to be scaled. The cutoff frequency is scaled from 1 radian/sec to w_0. If *m* is assumed to be the scaling factor, increase the resistors by *m* times, then the capacitor values have to decrease by 1/*m* times to keep the same cutoff frequency of 1 radian/sec. If the cutoff frequency is scaled to be w_0, then the capacitor values have to be decreased by 1 / w_0. The component values for the design goals are calculated in steps 3 and 4.

   $$R_1 = R_{1n} \times m,\ R_2 = R_{2n} \times m$$

   $$C_1 = C_2 = \frac{C_{1n}}{m \times w_0}\text{F}$$

3. Set C_1 and C_2 to 10nF, then calculate *m*.

   $$w_0 = 2 \times \pi \times 1\text{kHz},\ m = 15915.5$$

4. Select R_1 and R_2 based on *m*.

   $$R_1 = 0.707 \times 15915 = 11252\Omega \approx 11\text{k}\Omega\ (\text{Standard Value})$$

   $$R_2 = 1.414 \times 15915 = 22504\Omega \approx 23\text{k}\Omega\ (\text{Standard Value})$$

5. Calculate the minimum required GBW and SR for f_{max}.

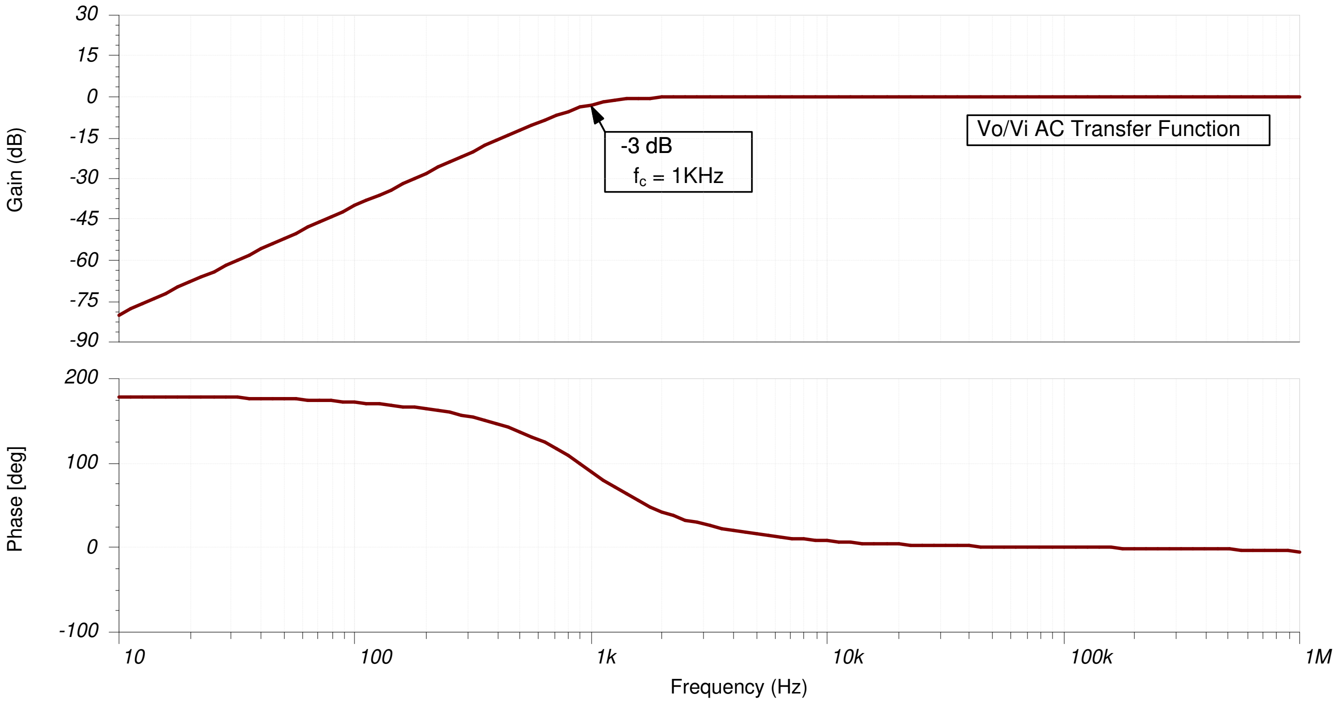
   $$GBW = 100 \times \text{Gain} \times f_{max} = 100 \times 1 \times 10\text{kHz} = 1\text{MHz}$$

   $$SR = 2 \times \pi \times f_{max} \times V_{ipeak} = 2 \times \pi \times 10\text{kHz} \times 2.45\text{V} = 0.154\frac{\text{V}}{\mu\text{s}}$$

   The TLV9062 device has a GBW of 10MHz and SR of 6.5V/µs, so it meets these requirements.

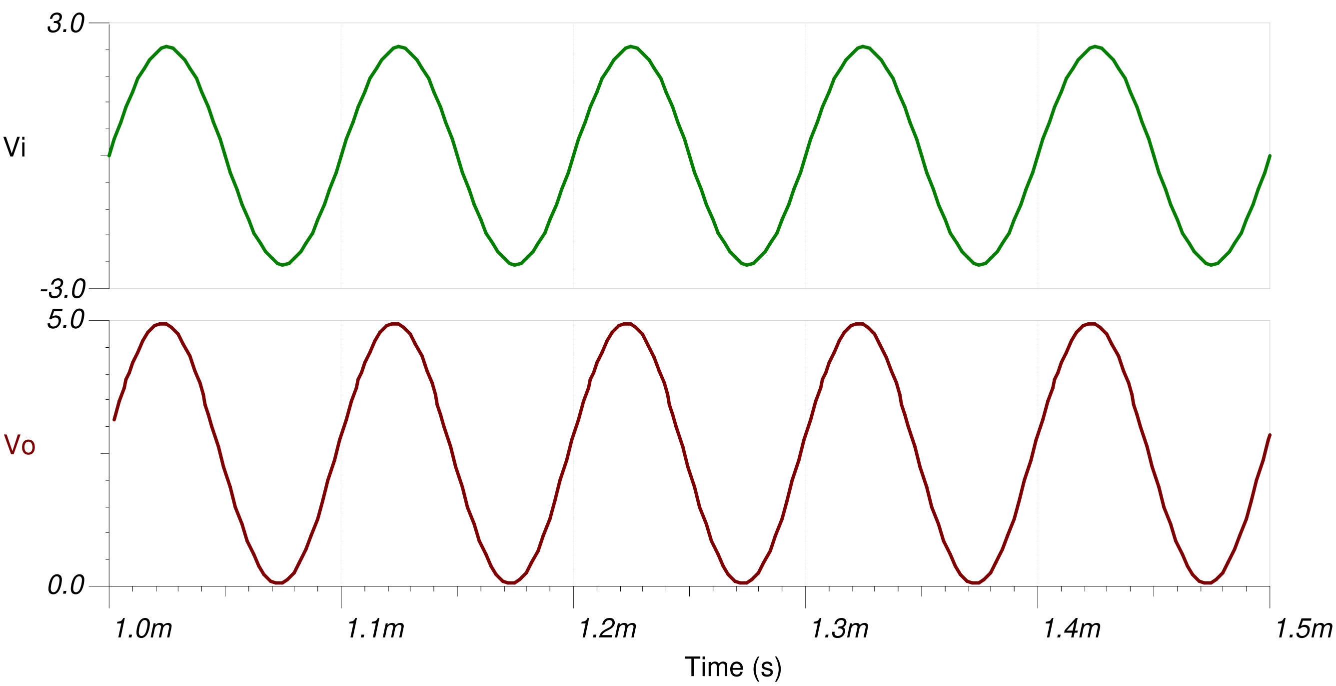
Design Simulations

AC Simulation Results

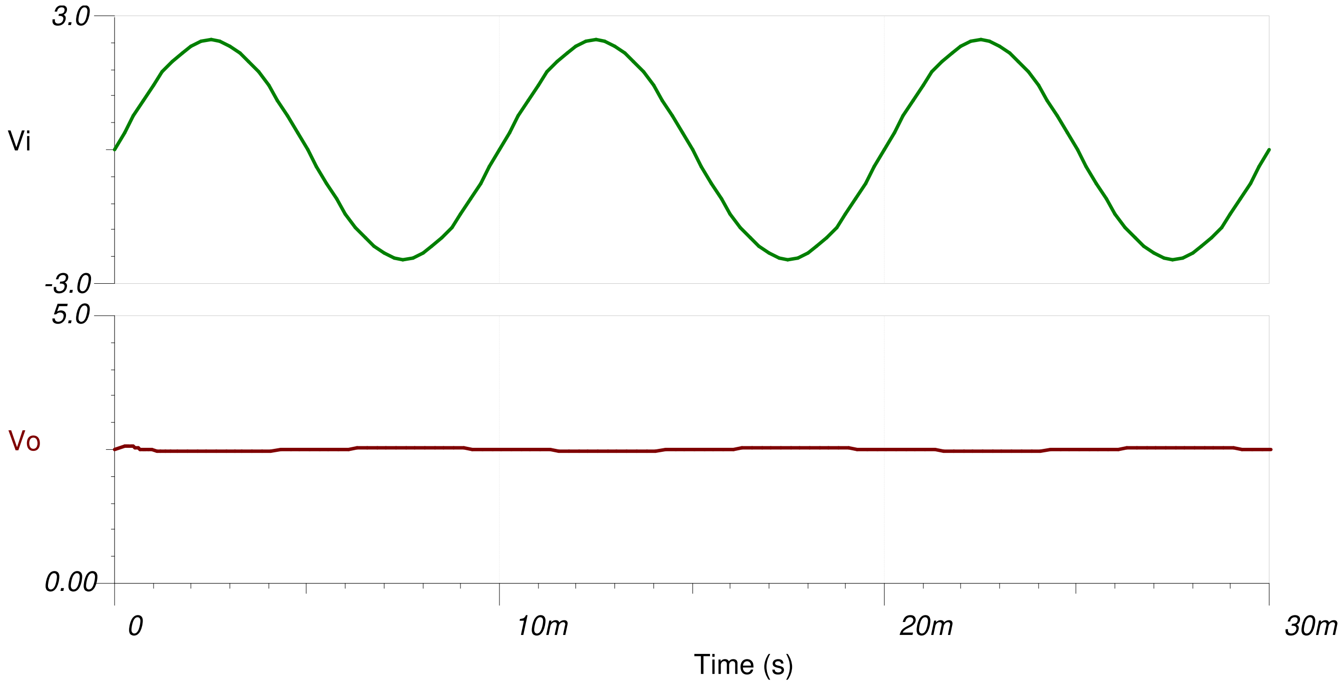


Transient Simulation Results

The following image shows the filter output in response to a ± 2.5-V, 10-kHz input signal (gain is 1V / V).



The following image shows the filter output in response to a ± 2.5-V, 10-Hz input signal (gain is 0.014V / V).



Design References

1. See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.
2. SPICE Simulation File - SBOMB38.
3. TI Precision Labs

Design Featured Op Amp

TLV9062	
Vss	1.8V to 5.5V
VinCM	Rail-to-Rail
Vout	Rail-to-Rail
Vos	0.3mV
Iq	538µA
Ib	0.5pA
UGBW	10MHz
SR	6.5V / µs
#Channels	1, 2, 4
www.ti.com/product/TLV9062	

Design Alternate Op Amp

	TLV316	OPA325
Vss	1.8V to 5.5V	2.2V to 5.5V
VinCM	Rail-to-Rail	Rail-to-Rail
Vout	Rail-to-Rail	Rail-to-Rail
Vos	0.75mV	0.150mV
Iq	400µA	650µA
Ib	10pA	0.2pA
UGBW	10MHz	10MHz
SR	6V / µs	5V / µs
#Channels	1, 2, 4	1, 2, 4
	www.ti.com/product/OPA316	www.ti.com/product/OPA325