

# 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

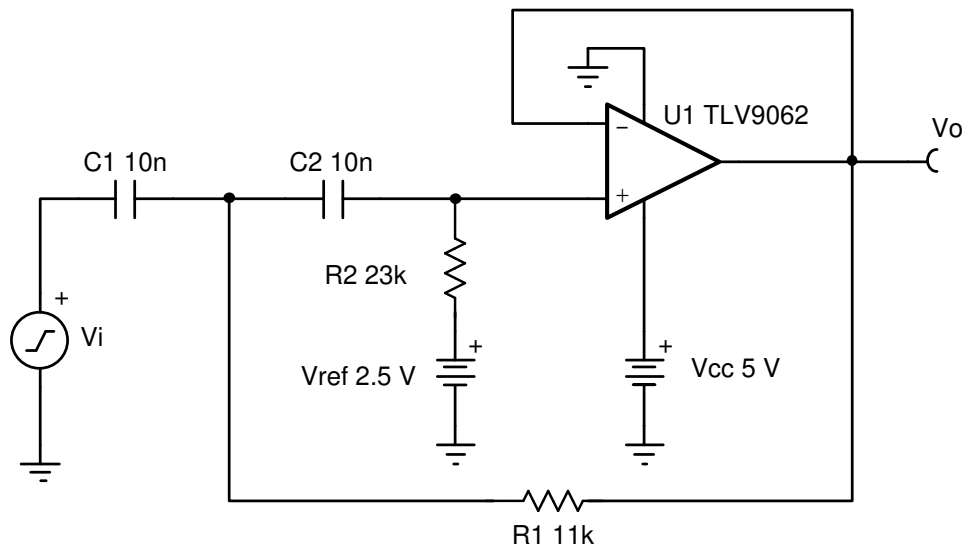
  

Gain	Cutoff Frequency ( $f_c$ )	Max Frequency ( $f_{max}$ )	$V_{ref}$
1V/V	1kHz	10kHz	2.5V

Design Description

The Butterworth Sallen-Key (SK) high-pass (HP) filter is a 2nd-order active filter.  $V_{ref}$  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,

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

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  $\omega_c$  to 1 radian/sec (or  $f_c = 1 / (2 \times \pi)$  Hz). For the second-order Butterworth filter, (see the *Butterworth Filter Table* in the [Active Low-Pass Filter Design Application Report](#)).

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

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

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  $\omega_0$ . 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  $\omega_0$ , then the capacitor values have to be decreased by  $1 / \omega_0$ . The component values for the design goals are calculated in steps 3 and 4.

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

$$C_1 = C_2 = \frac{C_{1n}}{m \times \omega_0} \text{ F}$$

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

$$\omega_0 = 2 \times \pi \times 1\text{kHz}, \quad m = 15915.5$$

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  $f_{\max}$ .

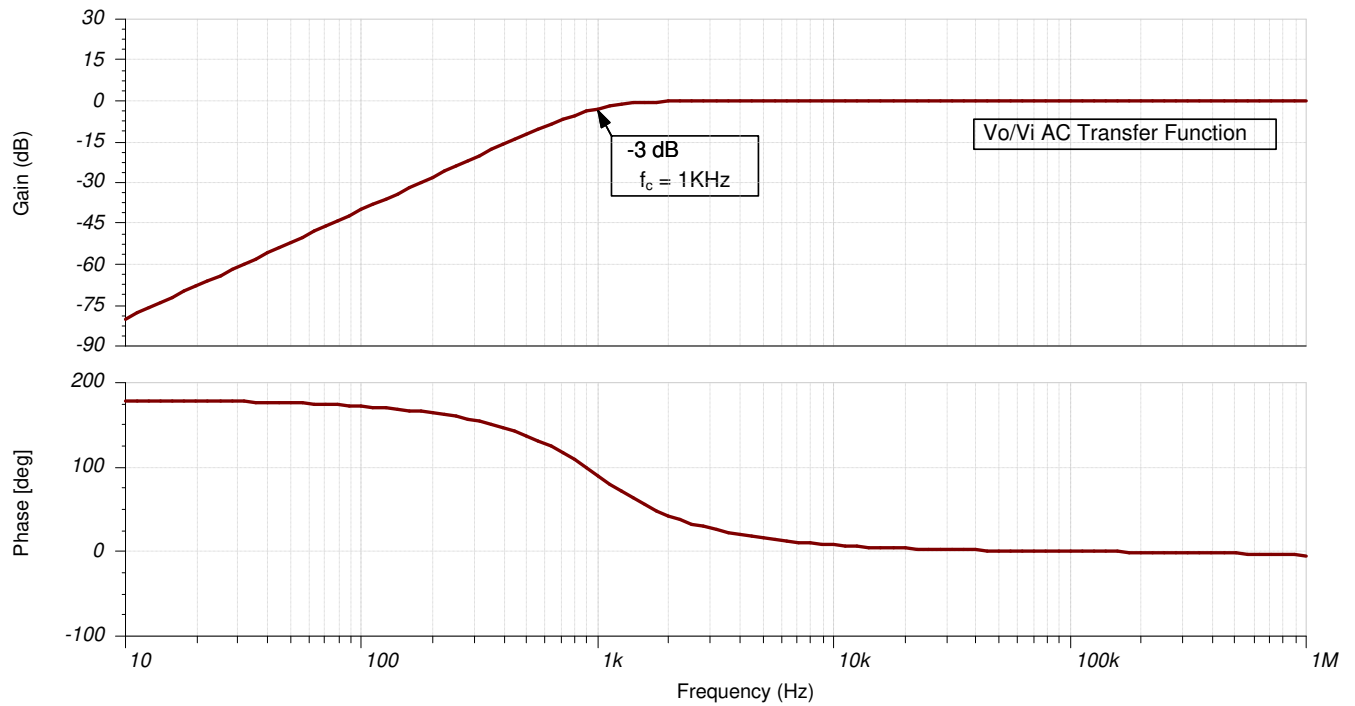
$$\text{GBW} = 100 \times \text{Gain} \times f_{\max} = 100 \times 1 \times 10\text{kHz} = 1\text{MHz}$$

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

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

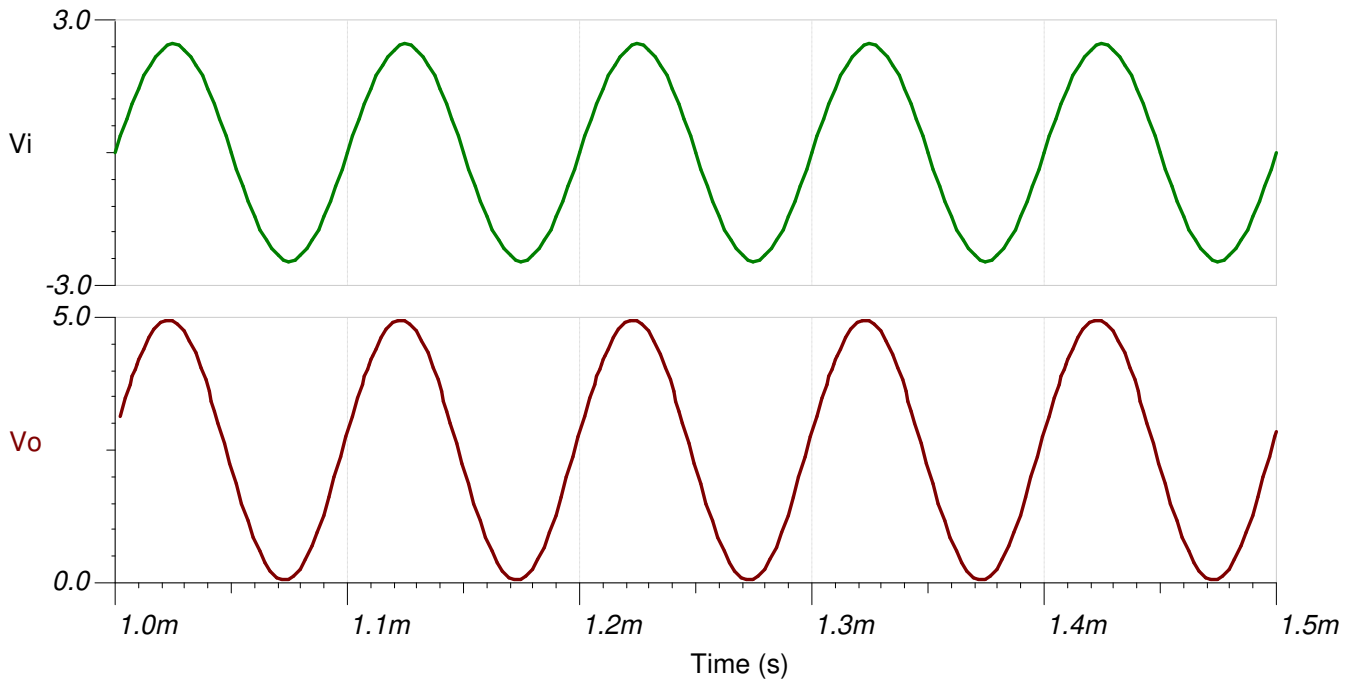
## Design Simulations

### AC Simulation Results

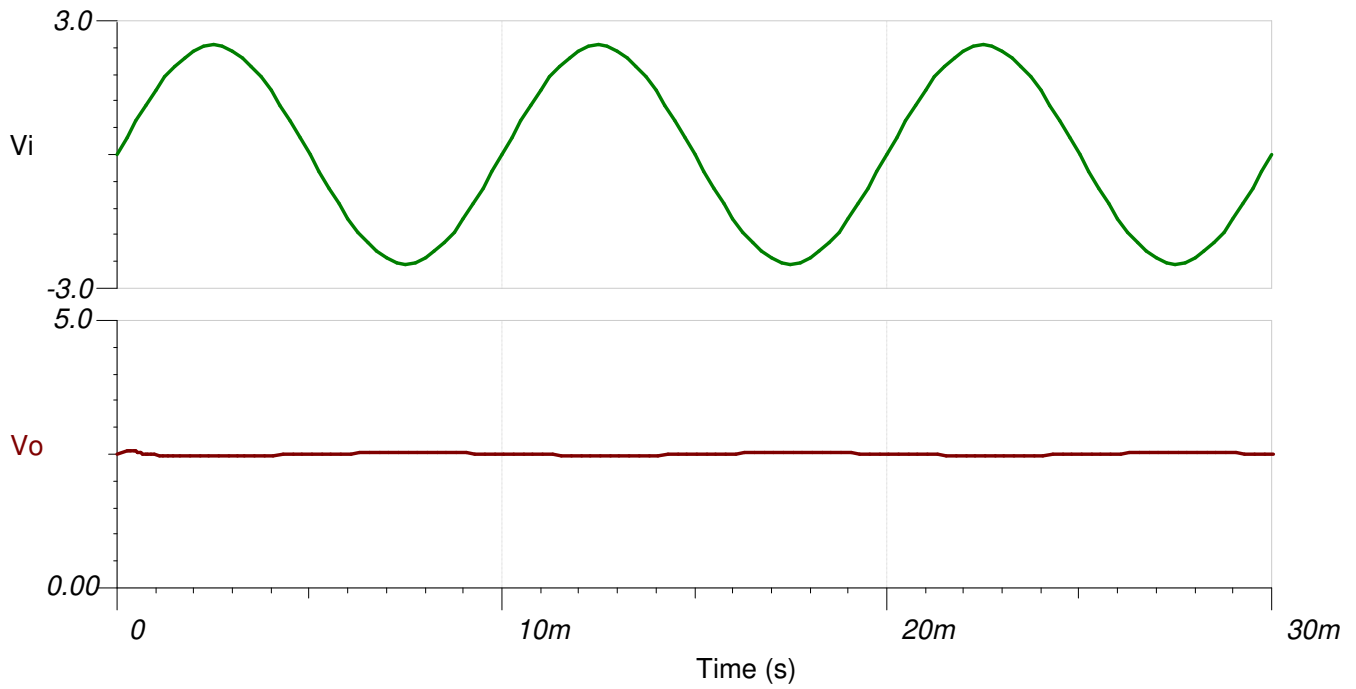


### Transient Simulation Results

The following image shows the filter output in response to a  $\pm 2.5\text{-V}$ , 10-kHz input signal (gain is 1V / V).



The following image shows the filter output in response to a  $\pm 2.5\text{-V}$ , 10-Hz input signal (gain is  $0.014\text{V/V}$ ).



## 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	
<b>Vss</b>	1.8V to 5.5V
<b>VinCM</b>	Rail-to-Rail
<b>Vout</b>	Rail-to-Rail
<b>Vos</b>	0.3mV
<b>Iq</b>	538 $\mu$ A
<b>Ib</b>	0.5pA
<b>UGBW</b>	10MHz
<b>SR</b>	6.5V / $\mu$ s
<b>#Channels</b>	1, 2, 4
<a href="http://www.ti.com/product/TLV9062">www.ti.com/product/TLV9062</a>	

## Design Alternate Op Amp

	TLV316	OPA325
<b>Vss</b>	1.8V to 5.5V	2.2V to 5.5V
<b>VinCM</b>	Rail-to-Rail	Rail-to-Rail
<b>Vout</b>	Rail-to-Rail	Rail-to-Rail
<b>Vos</b>	0.75mV	0.150mV
<b>Iq</b>	400 $\mu$ A	650 $\mu$ A
<b>Ib</b>	10pA	0.2pA
<b>UGBW</b>	10MHz	10MHz
<b>SR</b>	6V / $\mu$ s	5V / $\mu$ s
<b>#Channels</b>	1, 2, 4	1, 2, 4
	<a href="http://www.ti.com/product/OPA316">www.ti.com/product/OPA316</a>	<a href="http://www.ti.com/product/OPA325">www.ti.com/product/OPA325</a>

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