

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



Amplifiers

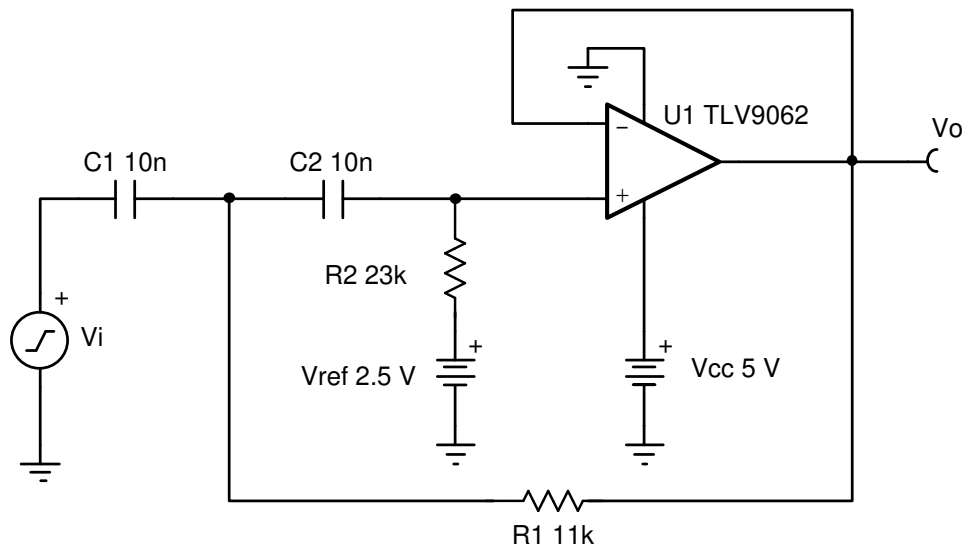
Input		Output		Supply	
V_{iMin}	V_{iMax}	V_{oMin}	V_{oMax}	V_{cc}	V_{ee}
-2.45V	+2.45V	0.05V	4.95V	5V	0V

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 ω_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 ω_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 ω_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} .

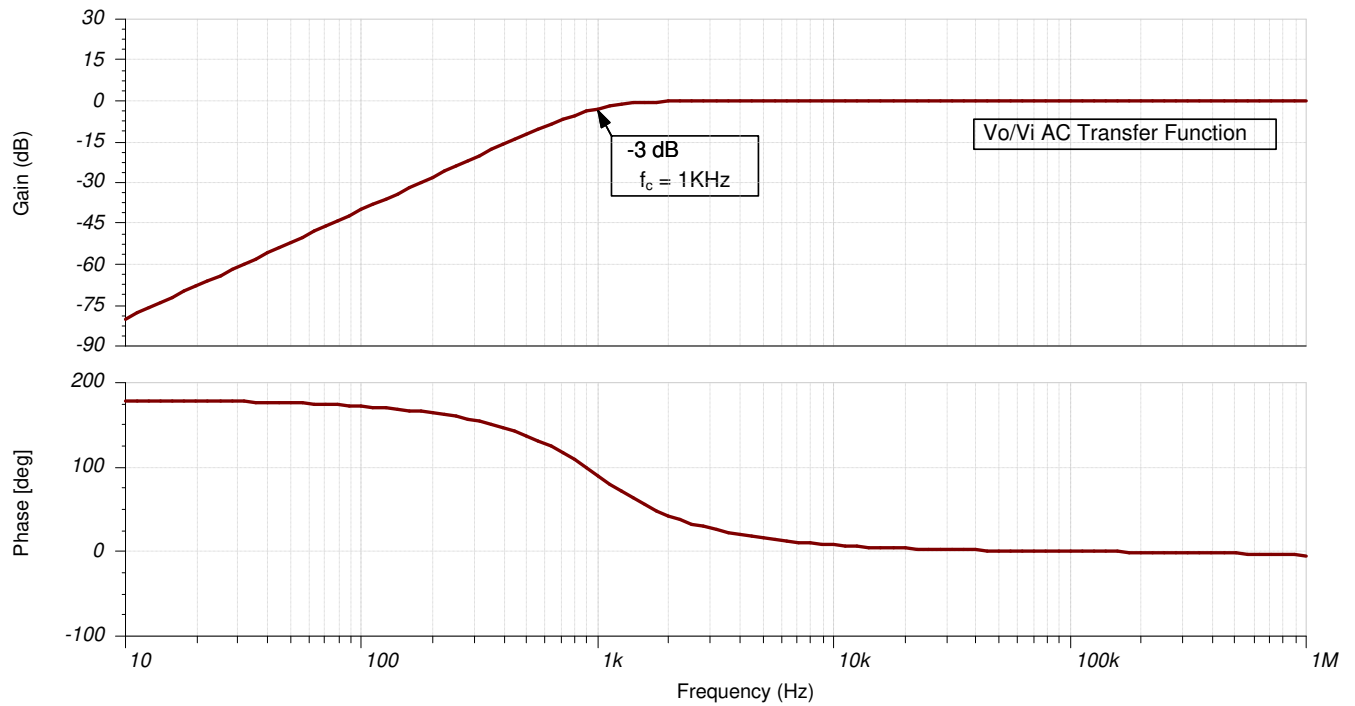
$$\text{GBW} = 100 \times \text{Gain} \times f_{\max} = 100 \times 1 \times 10\text{kHz} = 1\text{MHz}$$

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

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

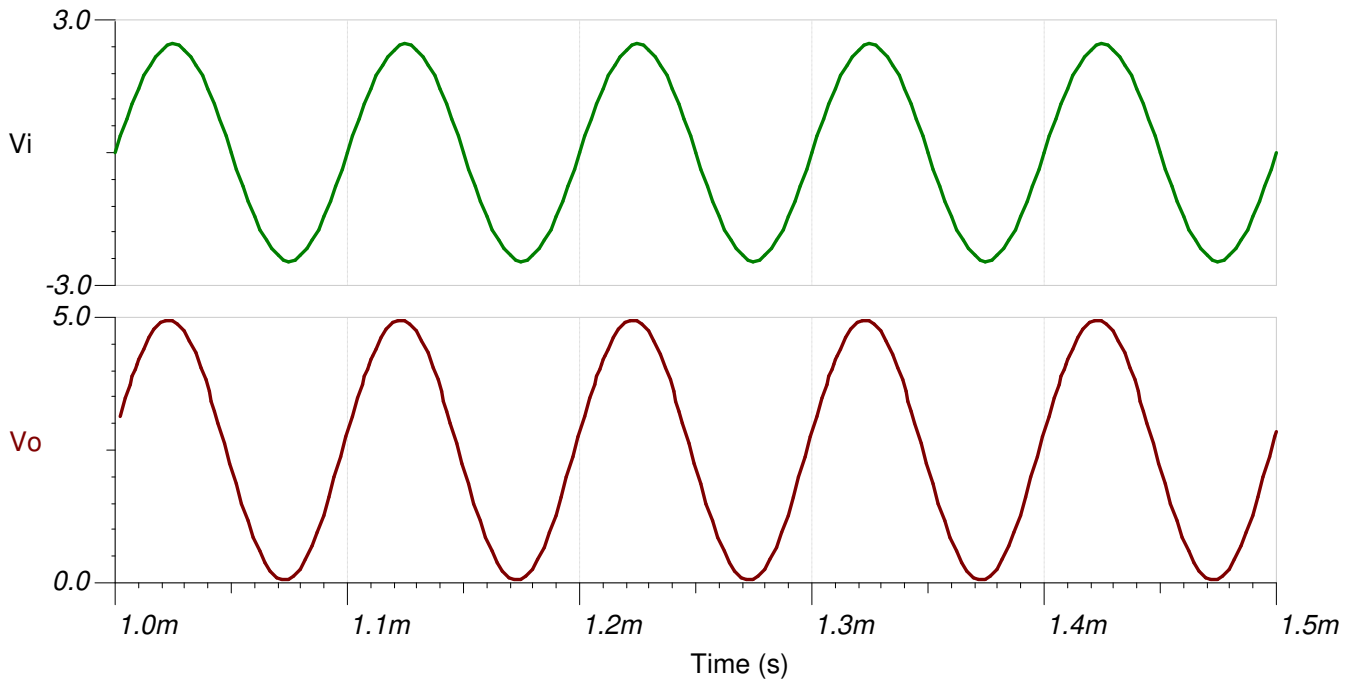
Design Simulations

AC Simulation Results

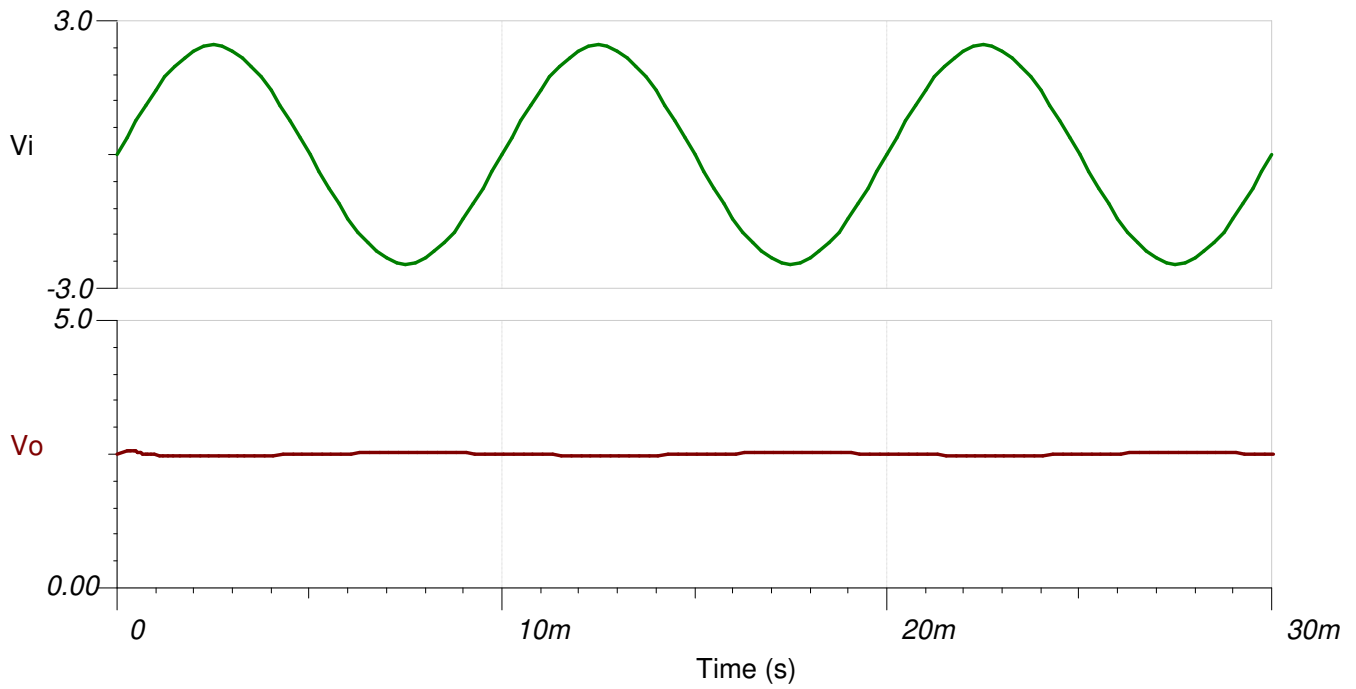


Transient Simulation Results

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 0.014V/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	538 μ A
Ib	0.5pA
UGBW	10MHz
SR	6.5V / μ s
#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	400 μ A	650 μ A
Ib	10pA	0.2pA
UGBW	10MHz	10MHz
SR	6V / μ s	5V / μ s
#Channels	1, 2, 4	1, 2, 4
	www.ti.com/product/OPA316	www.ti.com/product/OPA325

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2022, Texas Instruments Incorporated