Analog Engineer's Circuit

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

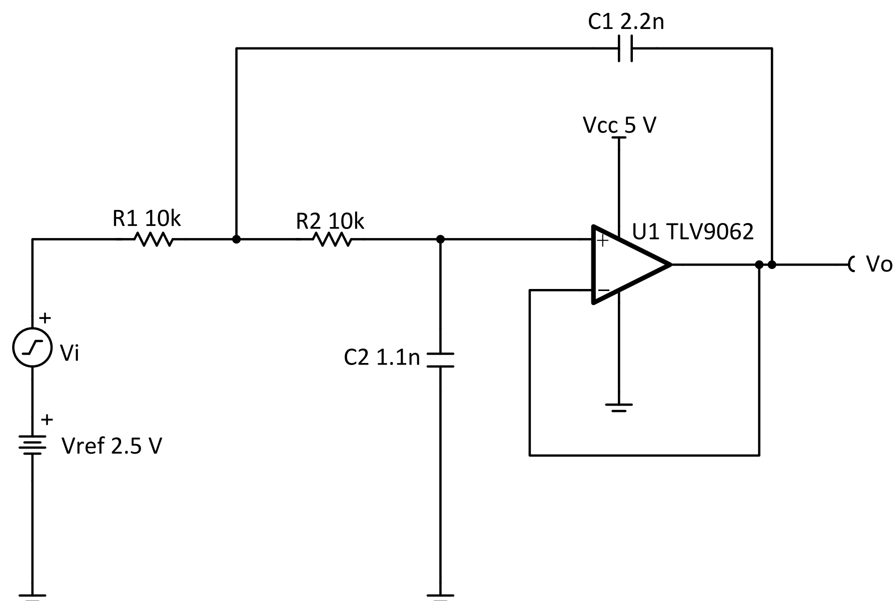
Amplifiers

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)	V_{ref}
1V/V	10kHz	2.5V

Design Description

The Butterworth Sallen-Key low-pass filter is a second-order active filter. V_{ref} provides a DC offset to accommodate for single-supply applications. A Sallen-Key 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).

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 second order Sallen-Key low-pass filter is given by:

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

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

Here,

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

1. Set normalized values of R_1 and R_2 (R_{1n} and R_{2n}) and calculate normalized values of C_1 and C_2 (C_{1n} and C_{2n}) by setting w_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*).

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

   $$\therefore C_{1n} = \sqrt{2} = 1.414\ \text{F},\ C_{2n} = \frac{1}{C_{1n}} = 0.707\ \text{F}$$

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_o. The component values for the design goals are calculated in steps 3 and 4.

   $$R_1 = R_{1n} \times m,\ \ R_2 = R_{2n} \times m \quad (6)$$

   $$C_1 = \frac{C_{1n}}{m \times \omega_0} = \frac{1.414}{m \times \omega_0}\text{F} \quad (7)$$

   $$C_2 = \frac{C_{2n}}{m \times \omega_0} = \frac{0.707}{m \times \omega_0}\text{F} \quad (8)$$

3. Set R1 and R2 values:

   $$m = 10000$$

   $$R_1 = (R_{1n} \times m) = 10\text{k}\Omega \quad (10)$$

   $$R_2 = (R_{2n} \times m) = 10\text{k}\Omega \quad (11)$$

4. Calculate C_1 and C_2 based on *m* and w_0.

$$\text{Given } \omega_0 = 2 \times \pi \times f_c, \text{ where } f_c = 10\text{kHz and } m = 10000 = 10\text{ k}$$

$$C_1 = \frac{1.414}{m \times \omega_0}\text{ F} = \frac{1.414}{10\text{ k} \times 2 \times \pi \times 10\text{kHz}} = 2.25\text{nF} \approx 2.2\text{nF (Standard Value)}$$

$$C_2 = \frac{0.707}{m \times \omega_0}\text{ F} = \frac{0.707}{10\text{ k} \times 2 \times \pi \times 10\text{kHz}} = 1.125\text{nF} \approx 1.1\text{nF (Standard Value)}$$

5. Calculate the minimum required GBW and SR for f_c.

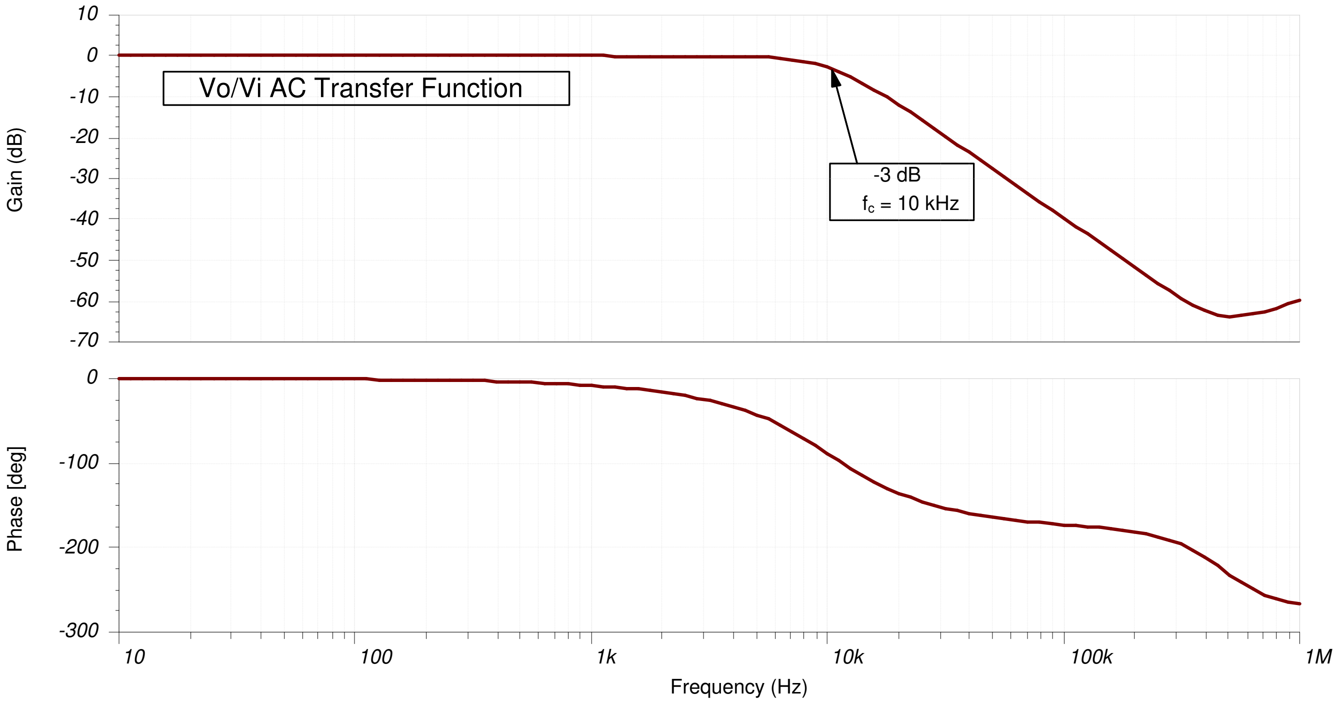
$$\text{GBW} = 100 \times \text{Gain} \times f_c = 100 \times 1 \times 10\text{kHz} = 1\text{MHz}$$

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

The TLV9062 device has a GBW of 10MHz and SR of 6.5V/µs, so the requirements are met.

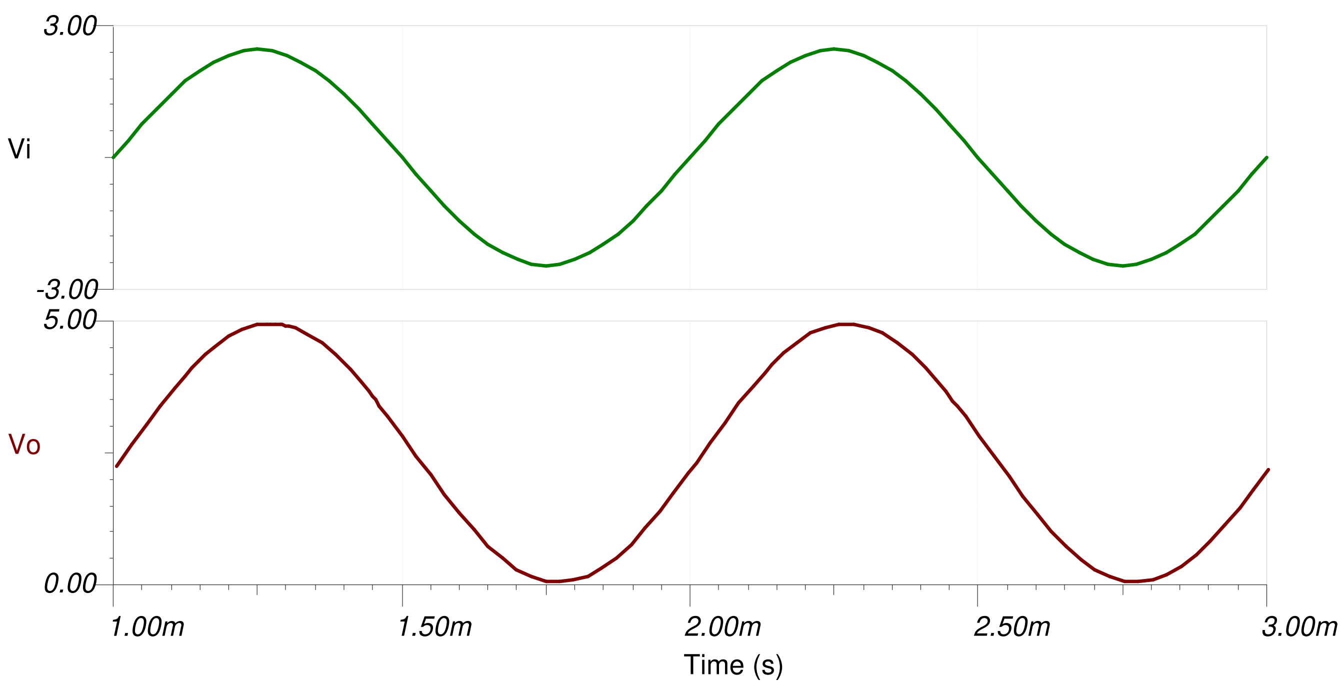
Design Simulations

AC Simulation Results

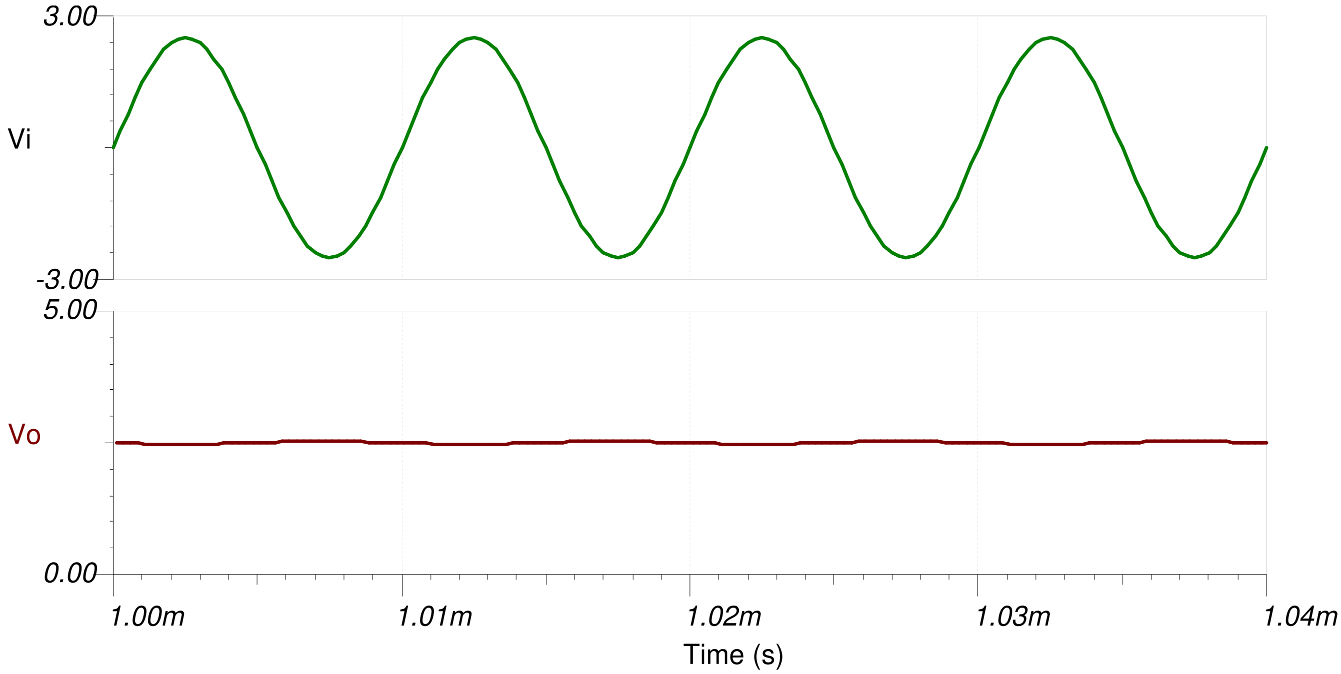


Transient Simulation Results

The following image shows the filter output in response to 5-Vpp, 1-kHz input signal (gain = 1V / V).



The following image shows the filter output in response to 5-Vpp, 100-kHz input signal (gain = 0.01 V/V).



Design References

1. See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.
2. SPICE Simulation File SBOC598.
3. TI Precision Labs.
4. *Active Low-Pass Filter Design Application Report*

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/TLV316	www.ti.com/product/OPA325