

Single-supply, 2nd-order, multiple feedback low-pass filter circuit



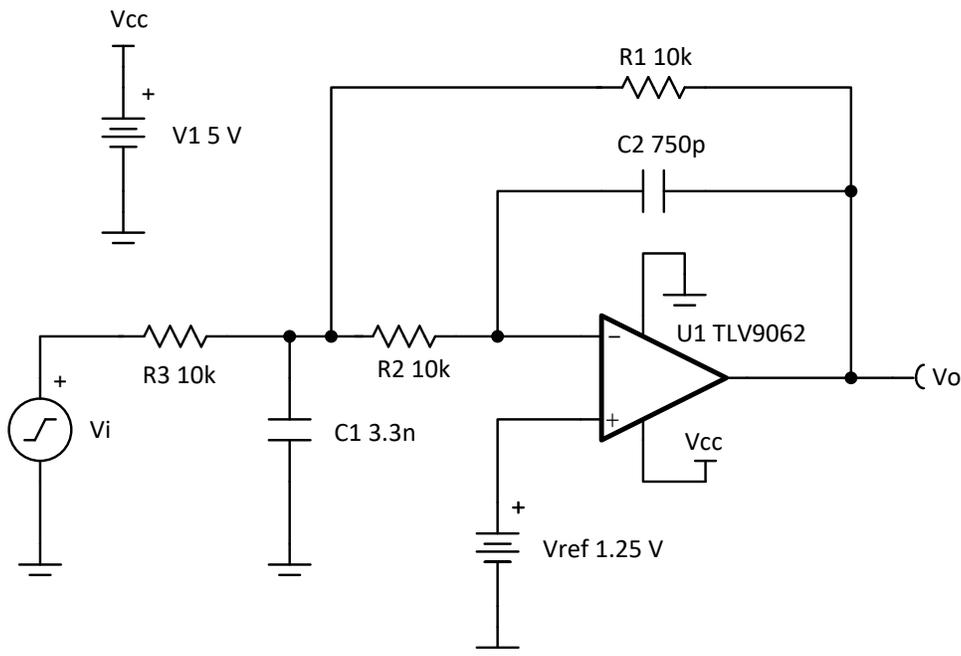
Amplifiers

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	1.25V

Design Description

The multiple-feedback (MFB) low-pass filter (LP filter) is a second-order active filter. V_{ref} provides a DC offset to accommodate for single-supply applications. This LP filter inverts the signal (Gain = $-1V/V$) for frequencies in the pass band. An MFB filter is preferable when the gain is high or when the Q-factor is large (for example, 3 or greater).



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 in design 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 a second-order MFB low-pass filter is given by:

$$H(s) = \frac{1}{s^2 + s \times \frac{1}{C_1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) + \frac{1}{R_1 \times R_2 \times C_1 \times C_2}}$$

$$H(s) = \frac{b_0}{s^2 + a_1 \times s + a_0}$$

$$\text{Here, } a_1 = \frac{1}{C_1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right), \quad a_0 = \frac{1}{R_1 \times R_2 \times C_1 \times C_2}$$

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

$$\omega_c = 1 \frac{\text{radian}}{\text{second}} \rightarrow a_0 = 1, a_1 = \sqrt{2}, \text{ let } R_{1n} = R_{2n} = R_{3n} = 1$$

$$\text{Then } C_{1n} \times C_{2n} = 1 \text{ or } C_{2n} = \frac{1}{C_{1n}}, a_1 = \frac{3}{C_{1n}} = \sqrt{2}$$

$$\therefore C_{1n} = \frac{3}{\sqrt{2}} = 2.1213 \text{ F}, \quad C_{2n} = \frac{1}{C_{1n}} = 0.4714 \text{ F}$$

2. Scale the component values and cutoff frequency. The resistor values are very small and capacitors values are unrealistic, hence these must be scaled. The cutoff frequency is scaled from 1 radian/second 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/second. 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.

$$R_1 = R_{1n} \times m, \quad R_2 = R_{2n} \times m, \quad R_3 = R_{3n} \times m$$

$$C_1 = \frac{C_{1n}}{m \times \omega_0} = \frac{2.1213}{m \times \omega_0} \text{ F}$$

$$C_2 = \frac{C_{2n}}{m \times \omega_0} = \frac{0.4714}{m \times \omega_0} \text{ F}$$

3. Set R_1 , R_2 , and R_3 to 10k Ω .

$$R_1 = R_{1n} \times m = 10\text{k}\Omega, \quad R_2 = R_{2n} \times m = 10\text{k}\Omega, \quad R_3 = R_{3n} \times m = 10\text{k}\Omega$$

$$\text{Therefore, } m = 10000$$

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

$$C_1 = \frac{2.1213}{m \times \omega_0} \text{ F} = \frac{2.1213}{10\text{k} \times 2 \times \pi \times 10\text{kHz}} = 3.376\text{nF} \approx 3.3\text{nF (Standard Value)}$$

$$C_2 = \frac{0.4714}{m \times \omega_0} \text{ F} = \frac{0.4714}{10\text{k} \times 2 \times \pi \times 10\text{kHz}} = 0.75\text{nF} \approx 0.75\text{nF (Standard Value)}$$

5. Calculate the minimum required GBW and SR for f_c . Be sure to use the noise gain for GBW calculations. Do not use the signal gain of $-1V/V$.

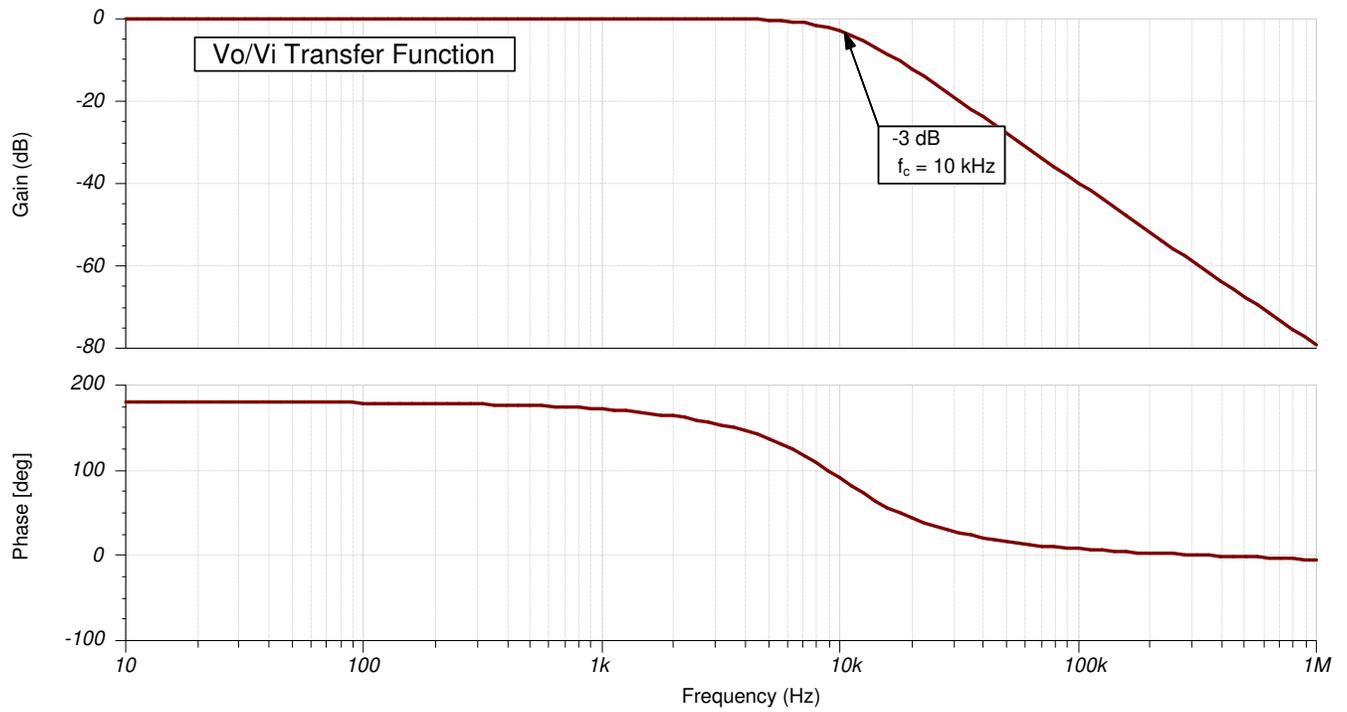
$$\text{GBW} = 100 \times \text{Noise Gain} \times f_c = 100 \times 2 \times 10\text{kHz} = 2\text{MHz}$$

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

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

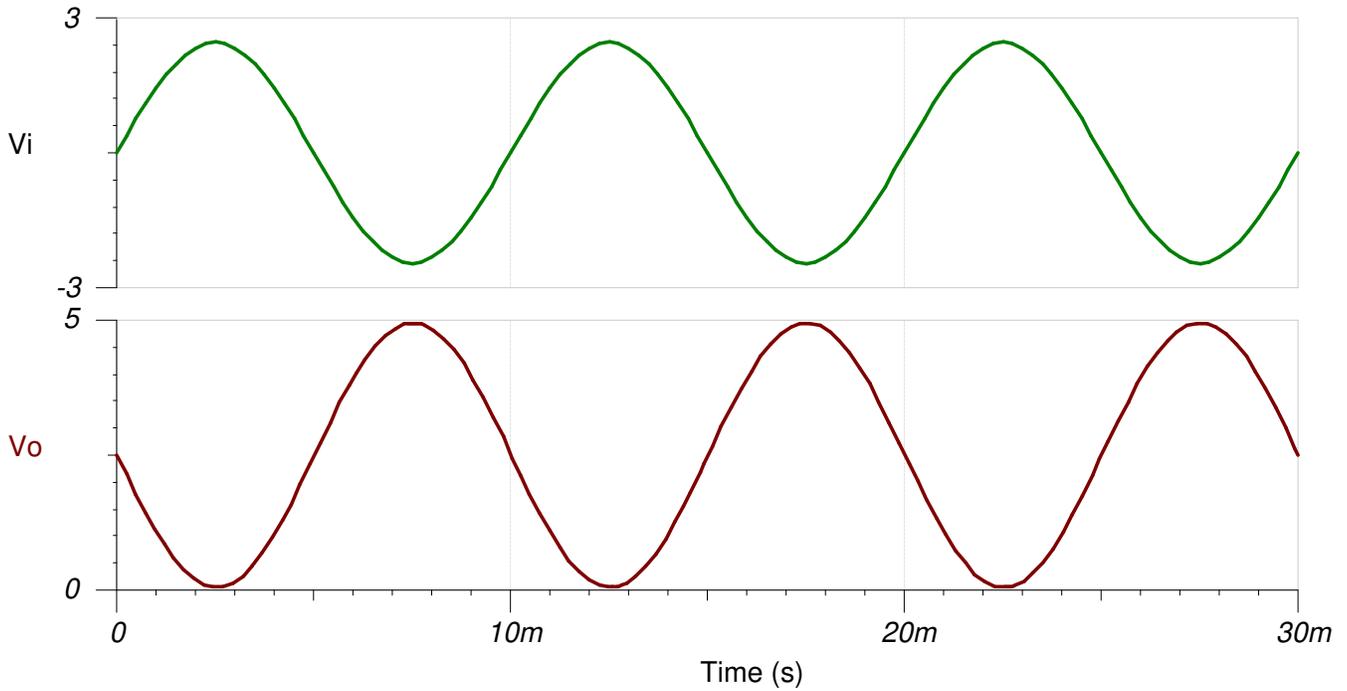
Design Simulations

AC Simulation Results

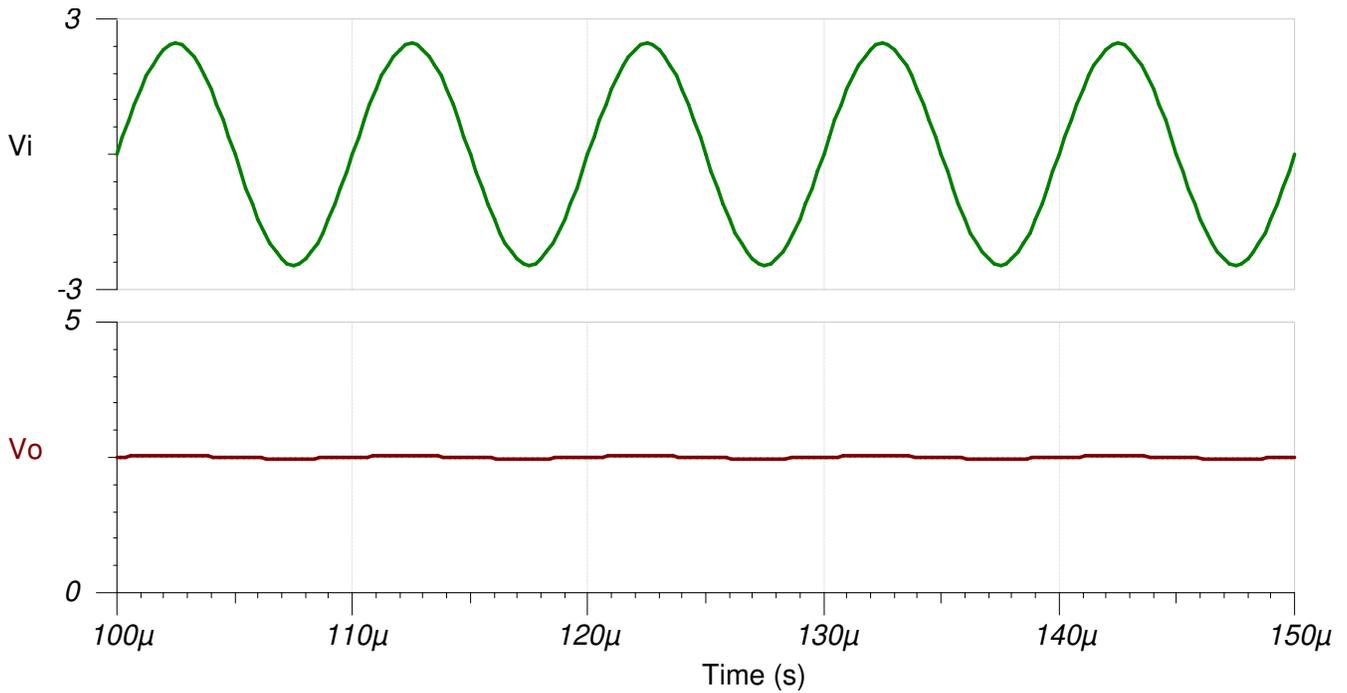


Transient Simulation Results

The following image shows the filter output in response to a $5\text{-}V_{pp}$, 100-Hz input signal (gain = $-1V/V$).



The following image shows the filter output in response to a $5\text{-}V_{pp}$, 10-kHz input signal (gain = $-0.01V/V$).



Design References

1. See [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.
2. SPICE Simulation File [SBOC597](#)
3. [TI Precision Labs](#).
4. [Active Low-Pass Filter Design Application Report](#)

Design Featured Op Amp

TLV9062	
V_{ss}	1.8V to 5.5V
V_{inCM}	Rail-to-Rail
V_{out}	Rail-to-Rail
V_{os}	0.3mV
I_q	538μA
I_b	0.5pA
UGBW	10MHz
SR	6.5V/μs
#Channels	1, 2, 4
www.ti.com/product/TLV9062	

Design Alternate Op Amp

	TLV316	OPA325
V_{ss}	1.8V to 5.5V	2.2V to 5.5V
V_{inCM}	Rail-to-Rail	Rail-to-Rail
V_{out}	Rail-to-Rail	Rail-to-Rail
V_{os}	0.75mV	0.150mV
I_q	400μA	650μA
I_b	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

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