Analog Engineer's Circuit

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

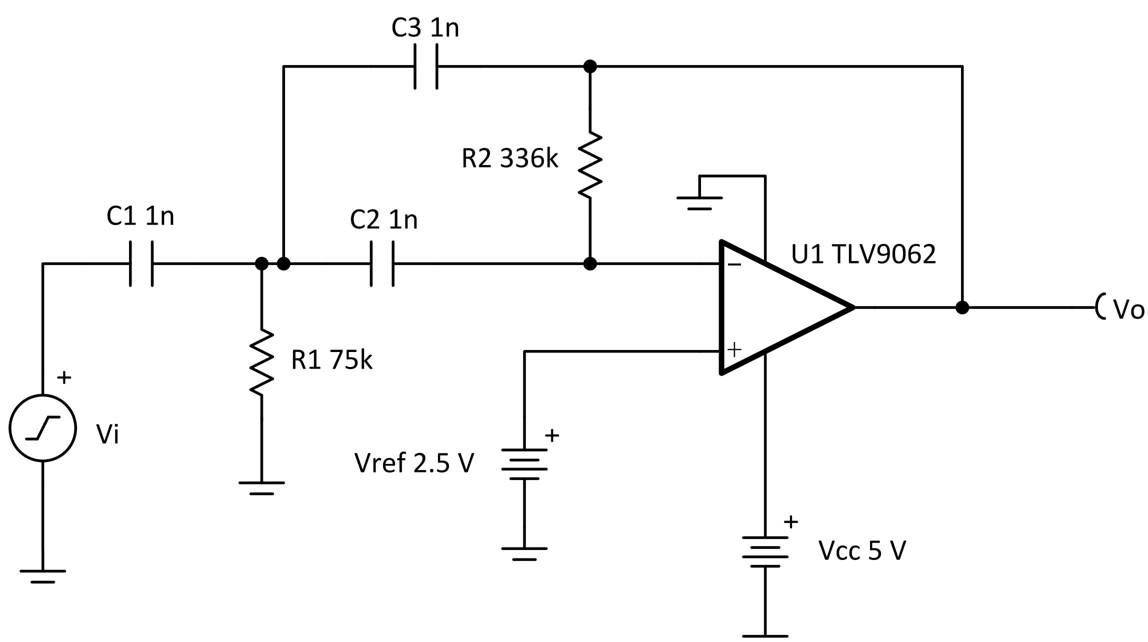
Amplifiers

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 multiple-feedback (MFB) high-pass (HP) filter is a 2nd-order active filter. V_{ref} provides a DC offset to accommodate for single-supply applications. This HP 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).
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.

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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 2nd-order MFB high pass filter is given by:

$$H(s) = \frac{-s^2\frac{C_1}{C_3}}{s^2 + s\frac{C_1 + C_2 + C_3}{R_2 \times C_2 \times C_3} + \frac{1}{R_1 \times R_2 \times C_2 \times C_3}}$$

$$H(s) = \frac{-s^2\frac{C_1}{C_3}}{s^2 + a_1 \times s + a_0}$$

$$\text{Here,}\ \ a_1 = \frac{C_1 + C_2 + C_3}{R_2 \times C_2 \times C_3},\ \ a_0 = \frac{1}{R_1 \times R_2 \times C_2 \times C_3} \qquad (3)$$

1. Set normalized values of C_1, C_2, and C_3 (C_{1n}, C_{2n}, and C_{3n}) and calculate normalized values of R_1 and R_2 (R_{1n} and R_{2n}) by setting w_c to 1radian/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*).

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

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

$$\therefore R_{2n} = 2.1213,\ \ R_{1n} = \frac{1}{R_{2n}} = 0.4714$$

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 we assume *m* 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 we scale the cutoff frequency 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 step 3 and 4.

$$R_1 = R_{1n} \times m = (0.4714 \times m),\ \ R_2 = R_{2n} \times m = (2.1213 \times m)$$

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

$$C_2 = \frac{C_{2n}}{m \times \omega_0} = \frac{1}{m \times \omega_0}\text{F}$$

$$C_3 = \frac{C_{3n}}{m \times \omega_0} = \frac{1}{m \times \omega_0}\text{F}$$

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3. Set C_1, C_2, and C_3 to 1nF and calculate m.

   Given $\omega_0 = 2 \times \pi \times f_c$, where $f_c = 1\text{kHz}$,

   $$C_1 = C_2 = C_3 = \frac{1}{m \times \omega_0}\text{F} = \frac{1}{m \times 2 \times \pi \times 1\text{kHz}}$$

   So, $m = 159155$

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

   $$R_1 = R_{1n} \times m = 0.4714 \times 159155 \approx 75\text{k}\Omega \text{ (Standard Value)}$$

   $$R_2 = R_{2n} \times m = 2.1213 \times 159155 \approx 336\text{k}\Omega \text{ (Standard Value)}$$

5. Calculate minimum required GBW and SR for f_{max}. Be sure to use the noise gain for GBW calculations. Do not use the signal gain of –1V/V.

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

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

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

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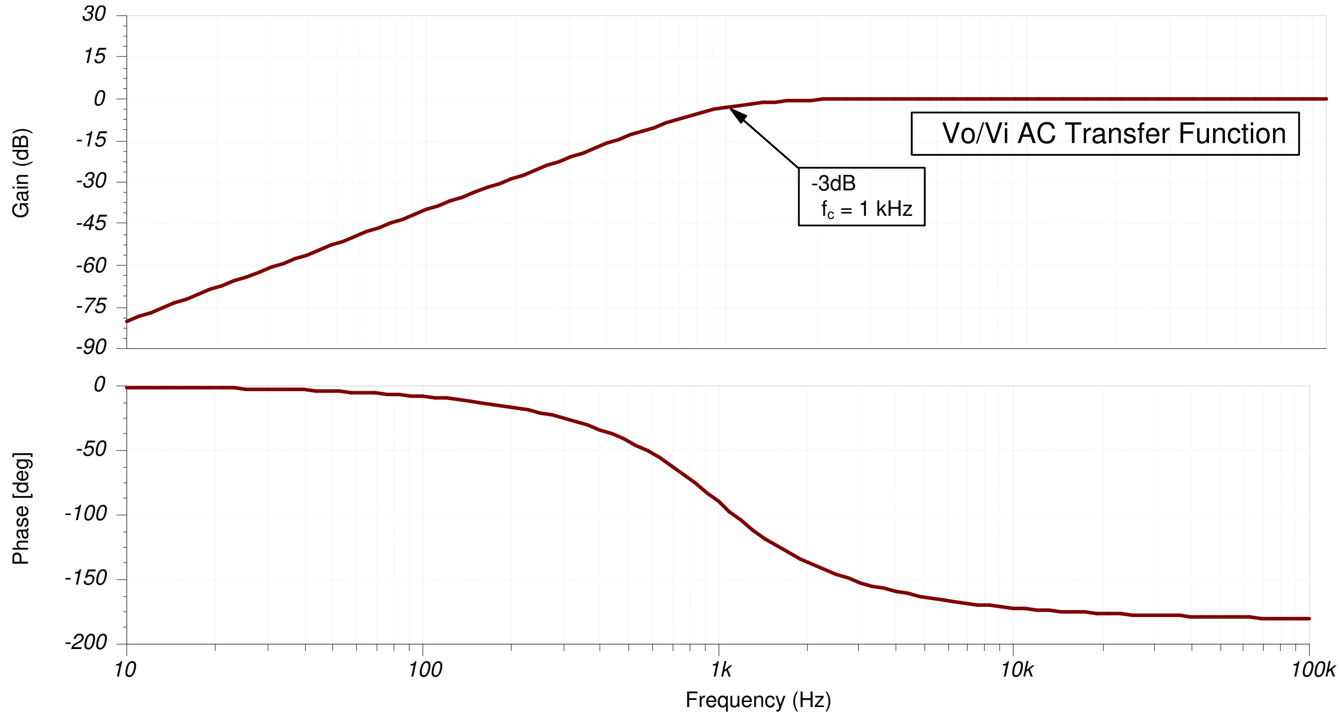
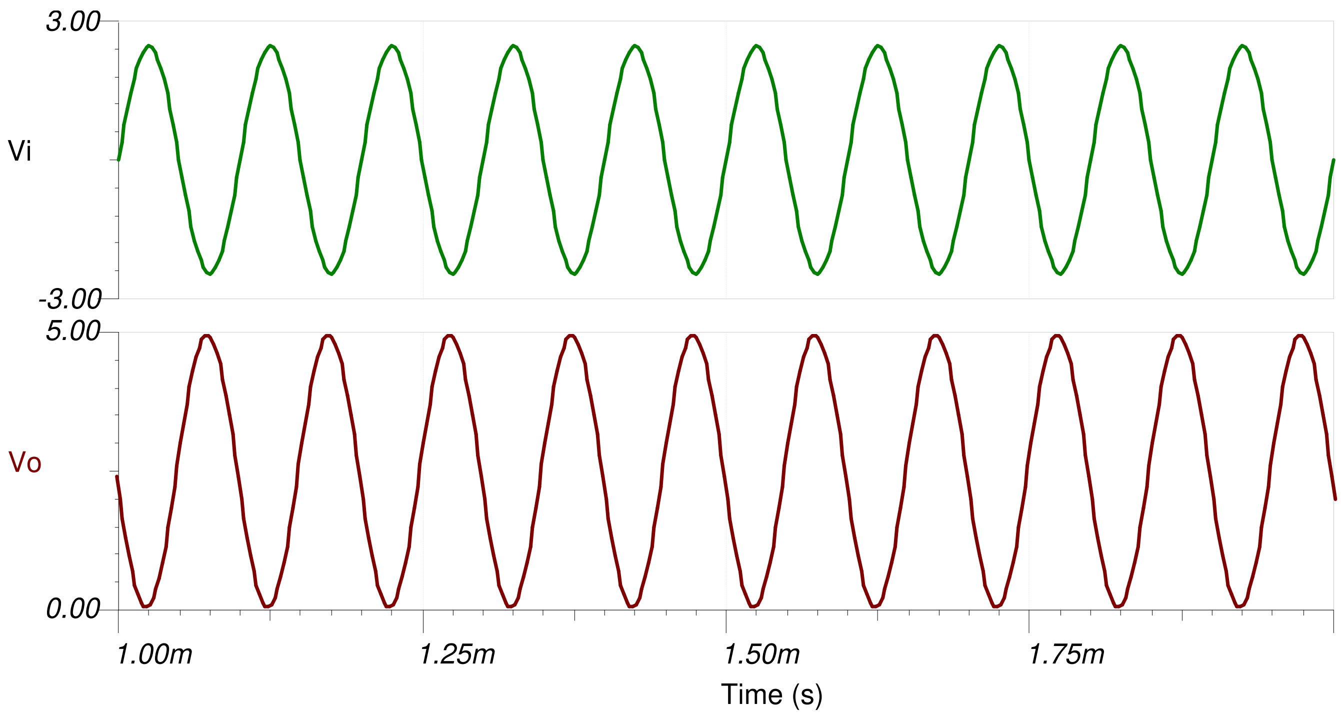
Design Simulations

AC Simulation Results



Transient Simulation Results



Filter Output in Response to a 5-V_{pp}, 10-kHz Input-Signal (Gain = –1V/V).

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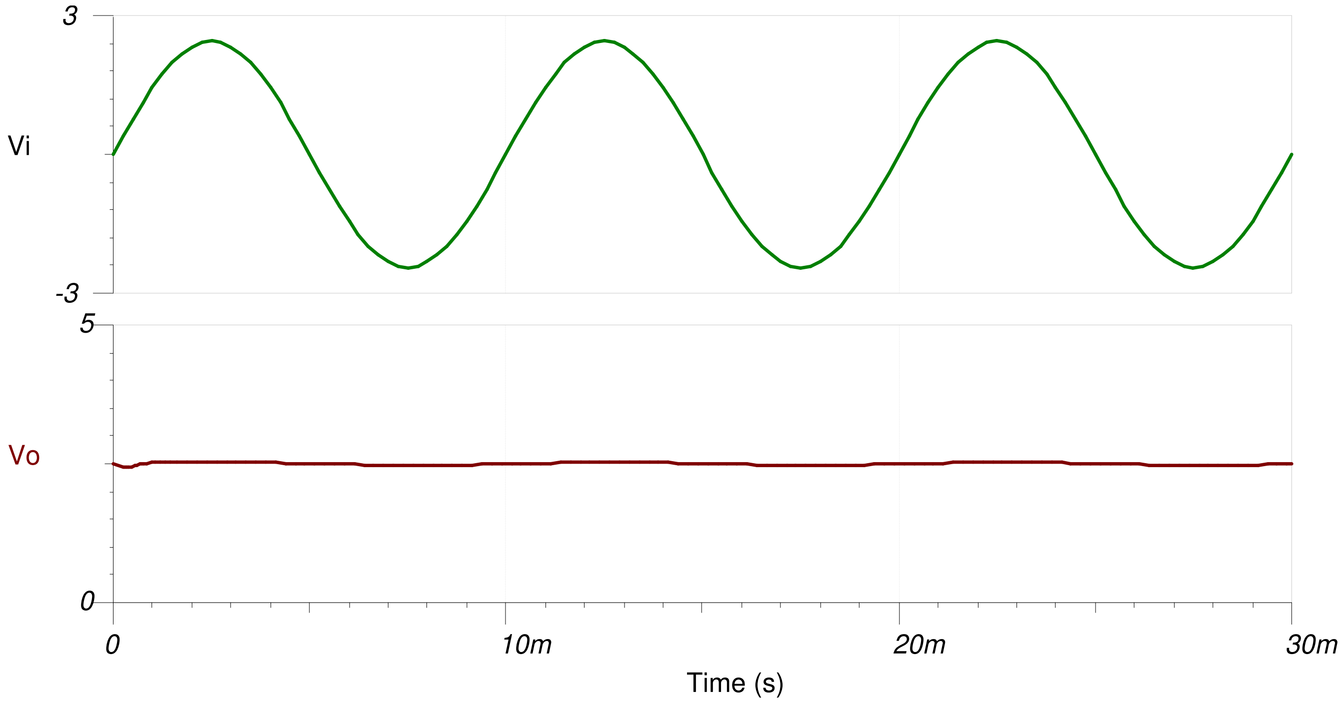

Filter Output in Response to a 5-V_{pp}, 100-Hz Input-Signal (Gain = –0.01V/V)

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Design References

1. See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.
2. SPICE Simulation File: SBOC599.
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
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
V_{ss}	1.8V to 5.5V	2.2V to 5.5V
V_{inCM}	Rail-to-Rail	Rail-to-Rail
Vout	Rail-to-Rail	Rail-to-Rail
V_{os}	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

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