Analog Engineer's Circuit

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

**Amplifiers**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{i\text{Min}}$</td>
<td>$V_{i\text{Max}}$</td>
<td>$V_{o\text{Min}}$</td>
</tr>
<tr>
<td>–2.45V</td>
<td>+2.45V</td>
<td>0.05V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gain</th>
<th>Cutoff Frequency ($f_c$)</th>
<th>$V_{\text{ref}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1V/V</td>
<td>10kHz</td>
<td>2.5V</td>
</tr>
</tbody>
</table>

**Design Description**

The Butterworth Sallen-Key low-pass filter is a second-order active filter. $V_{\text{ref}}$ 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 $V_{\text{ref}}$ 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:

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

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

Here,

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

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 \(\omega_c\) 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).

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

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

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 \(\omega_0\). 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.

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

\[
C_1 = \frac{C_{1n}}{m \times \omega_0} = \frac{1.414}{m \times \omega_0} \text{ F}
\]

\[
C_2 = \frac{C_{2n}}{m \times \omega_0} = \frac{0.707}{m \times \omega_0} \text{ F}
\]

3. Set R1 and R2 values:

\[
m = 10000
\]

\[
R_1 = (R_{1n} \times m) = 10k\Omega
\]

\[
R_2 = (R_{2n} \times m) = 10k\Omega
\]
4. Calculate $C_1$ and $C_2$ based on $m$ and $w_0$.

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

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

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

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

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

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

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

AC Simulation Results

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

Transient Simulation Results
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

<table>
<thead>
<tr>
<th></th>
<th>TLV9062</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vss</td>
<td>1.8V to 5.5V</td>
</tr>
<tr>
<td>VinCM</td>
<td>Rail-to-Rail</td>
</tr>
<tr>
<td>Vout</td>
<td>Rail-to-Rail</td>
</tr>
<tr>
<td>Vos</td>
<td>0.3mV</td>
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<tr>
<td>Iq</td>
<td>538µA</td>
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<tr>
<td>Ib</td>
<td>0.5pA</td>
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<tr>
<td>UGBW</td>
<td>10MHz</td>
</tr>
<tr>
<td>SR</td>
<td>6.5V/µs</td>
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<tr>
<td>#Channels</td>
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</table>

Design Alternate Op Amp

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<th></th>
<th>TLV316</th>
<th>OPA325</th>
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</thead>
<tbody>
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<td>Vss</td>
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<td>2.2V to 5.5V</td>
</tr>
<tr>
<td>VinCM</td>
<td>Rail-to-Rail</td>
<td>Rail-to-Rail</td>
</tr>
<tr>
<td>Vout</td>
<td>Rail-to-Rail</td>
<td>Rail-to-Rail</td>
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<tr>
<td>Vos</td>
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<td>0.150mV</td>
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<tr>
<td>Iq</td>
<td>400µA</td>
<td>650µA</td>
</tr>
<tr>
<td>Ib</td>
<td>10pA</td>
<td>0.2pA</td>
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<tr>
<td>UGBW</td>
<td>10MHz</td>
<td>10MHz</td>
</tr>
<tr>
<td>SR</td>
<td>6V/µs</td>
<td>5V/µs</td>
</tr>
<tr>
<td>#Channels</td>
<td>1, 2, 4</td>
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</table>

www.ti.com/product/TLV9062

www.ti.com/product/TLV316

www.ti.com/product/OPA325
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