Active Filters - Revisited

Sources:

Electronic Devices
by
Thomas L. Floyd.

&

Electronic Devices and Circuit Theory
by
Robert L. Boylestad, Louis Nashelsky
Ideal and Practical Filters

Comparison of an ideal low-pass filter response (blue area) with actual response. Although not shown on log scale, response extends down to $f_c = 0$.

Idealized low-pass filter responses

$$BW = f_c$$

$$f_c = \frac{1}{2\pi RC}$$
Ideal and Practical Filters

Comparison of an ideal high-pass filter response (blue area) with actual response

Idealized high-pass filter responses

Basic high-pass circuit

\[ f_c = \frac{1}{2\pi RC} \]
Ideal and Practical Filters

Quality Factor (Q) of a band-pass filter is the ratio of the center frequency to the bandwidth.

\[ BW = f_{c2} - f_{c1} \]

\[ f_0 = \sqrt{f_{c1} f_{c2}} \]

\[ Q = \frac{f_0}{BW} \]

\[ Q = \frac{1}{DF} \]

The quality factor (Q) can also be expressed in terms of the damping factor (DF) of the filter as
Ideal and Practical Filters

Butterworth, Chebyshev, or Bessel response characteristics can be realized with most active filter circuit configurations by proper selection of certain component values.

The Butterworth Characteristic
- Provides a very flat amplitude response in the passband and a roll-off rate of -20 dB/decade/pole
- Phase response is not linear
- A pulse will cause overshoots on the output because each frequency component of the pulse’s rising and falling edges experiences a different time delay
- Normally used when all frequencies in the passband must have the same gain.
- Often referred to as a maximally flat response.

![Diagram showing amplitude response of Butterworth, Bessel, and Chebyshev filters]
Ideal and Practical Filters

Butterworth, Chebyshev, or Bessel response characteristics can be realized with most active filter circuit configurations by proper selection of certain component values.

The Chebyshev Characteristic
- Useful when a rapid roll-off is required
- Because it provides a roll-off rate greater than 20 dB/decade/pole
- Filters can be implemented with fewer poles and less complex circuitry for a given roll-off rate
- Characterized by overshoot or ripples in the passband (depending on the number of poles)
- and an even less linear phase response than the Butterworth.
Butterworth, Chebyshev, or Bessel response characteristics can be realized with most active filter circuit configurations by proper selection of certain component values.

**The Bessel Characteristic**
- Response exhibits a linear phase characteristic
- Meaning that the phase shift increases linearly with frequency
- Result is almost no overshoot on the output with a pulse input
- For this reason, filters with the Bessel response are used for filtering pulse waveforms without distorting the shape of the waveform.
Ideal and Practical Filters

- An active filter can be designed to have either a Butterworth, Chebyshev, or Bessel response characteristic regardless of whether it is a low-pass, high-pass, band-pass,
- The damping factor (DF) of an active filter circuit determines which response characteristic the filter exhibits
- A generalized active filter is shown in figure below
- Includes an amplifier, a negative feedback circuit, and a filter section
- Damping factor determined by negative feedback circuit is given by

\[
DF = 2 - \frac{R_1}{R_2}
\]
Ideal and Practical Filters

- Damping factor affects filter response by negative feedback action
- Any attempted increase or decrease in the output voltage is offset by the opposing effect of the negative feedback
- This tends to make the response curve flat in the passband of the filter if the value for the damping factor is precisely set
- By advanced mathematics, which we will not cover, values for the damping factor have been derived for various orders of filters to achieve the maximally flat response of the Butterworth characteristic

• The value of the damping factor required to produce a desired response characteristic depends on the order (number of poles) of the filter
• A pole, for our purposes, is simply a circuit with one resistor and one capacitor. The more poles a filter has, the faster its roll-off rate is
• To achieve a second-order Butterworth response, for example, the damping factor must be 1.414.
Ideal and Practical Filters

- To achieve a second-order Butterworth response, for example, the damping factor must be 1.414.
- To implement this damping factor, the feedback resistor ratio must be

\[
\frac{R_1}{R_2} = 2 - DF = 2 - 1.414 = 0.586
\]

- This ratio gives the closed-loop gain of the noninverting amplifier portion of the filter, derived as follows:

\[
A_{cl(NI)} = \frac{1}{B} = \frac{1}{R_2/(R_1 + R_2)} = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1 = 0.586 + 1 = 1.586
\]
Ideal and Practical Filters

• To produce a filter that has a steeper transition region it is necessary to add additional circuitry to the basic filter.
• Responses that are steeper than in the transition region cannot be obtained by simply cascading identical RC stages (due to loading effects)
• However, by combining an op-amp with frequency-selective feedback circuits, filters can be designed with roll-off rates of or more dB/decade
• Filters that include one or more op-amps in the design are called active filters
• These filters can optimize the roll-off rate or other attribute (such as phase response) with a particular filter design
• In general, the more poles the filter uses, the steeper its transition region will be
• The exact response depends on the type of filter and the number of poles
Ideal and Practical Filters

- The number of poles determines the roll-off rate of the filter
- A Butterworth response produces -20 dB/decade/pole
  - a first-order (one-pole) filter has a roll-off of -20 dB/decade
  - a second-order (two-pole) filter has a roll-off rate of -40 dB/decade
  - a third-order (three-pole) filter has a roll-off rate of -60 dB/decade …
- Generally, to obtain a filter with three poles or more, one-pole or two-pole filters are cascaded, as shown in figure below
- To obtain a third-order filter, for example, cascade a second-order and a first-order filter
- To obtain a fourth-order filter, cascade two second-order filters; and so on
- Each filter in a cascaded arrangement is called a stage or section.
Active Filters – Low-Pass Filters

A Single Pole Low-Pass Filter

\[ A_{cl(NI)} = \frac{R_1}{R_2} + 1 \]

\[ f_c = \frac{1}{2\pi RC} \]
Active Filters – Low-Pass Filters

\[ V_i = \frac{V_1}{R_1 + \frac{1}{j \omega C_1}} \Rightarrow V_i = \frac{V_1}{1 + j \omega R_1 C_1} \]

\[ i_o = \frac{V_o - V_i}{R_F} \approx \frac{V_i}{R_G} \Rightarrow V_o = \left(1 + \frac{R_F}{R_G}\right)V_i \]

Combining:

\[ V_o = \left(1 + \frac{R_F}{R_G}\right)\left(\frac{1}{1 + j \omega R_1 C_1}\right)V_1 \]
Active Filters – Low-Pass Filters

\[ \frac{V_o}{V_1} = A_v = \left(1 + \frac{R_F}{R_G}\right) \left(\frac{1}{1 + j\omega R_1 C_1}\right) \]

- **Real number (gain)**
- **Low-pass filter**
- >1 for a low-pass filter with voltage gain

\[ f_{OL} = \frac{1}{2\pi R_1 C_1} \]

- **cut-off frequency**
Active Filters – Low-Pass Filters

\[
\frac{V_o}{V_1} = A_v = \left(1 + \frac{R_F}{R_G}\right) \left(\frac{1}{1 + j\omega R_1 C_1}\right)
\]

- **Real number (gain)**
- **Low-pass filter**
- \(f_{OL} = \frac{1}{2\pi R_1 C_1}\)
  - cut-off frequency

>1 for a low-pass filter with voltage gain

[Diagram showing frequency response with -3 dB and -6 dB/octave markers.]
Active Filters – Low-Pass Filters
Active Filters – Low-Pass Filters

The Sallen-Key Low-Pass Filter

- There are two low-pass RC circuits that provide a roll-off of -40 dB/decade above the critical frequency (assuming a Butterworth characteristic)
- One RC circuit consists of $R_A$ and $C_A$ and the second circuit consists of $R_B$ and $C_B$
- A unique feature is the capacitor that provides feedback for shaping the response near the edge of passband
- If $R_A = R_B = R$ and $C_A = C_B = C$

$$f_c = \frac{1}{2\pi R A R B C_A C_B}$$

$$f_c = \frac{1}{2\pi RC}$$
Active Filters – Low-Pass Filters

Cascaded Low-Pass Filter

Third-order configuration

Fourth-order configuration
Ideal and Practical Filters

Values for the Butterworth response

<table>
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<tr>
<th>ORDER</th>
<th>ROLL-OFF DB/DECADE</th>
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<th>2ND STAGE</th>
<th>3RD STAGE</th>
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<td></td>
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<td>2</td>
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<td>−120</td>
<td>2</td>
<td>1.932</td>
<td>0.068</td>
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</table>

- Determine the capacitance values for a critical frequency of 2680 Hz if all the resistors in the RC low-pass circuits are 1.8 kΩ.
- Also select values for the feedback resistors to get a Butterworth response.
Ideal and Practical Filters

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<th>ROLL-OFF DB/DECADE</th>
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- Determine the capacitance values for a critical frequency of 2680 Hz if all the resistors in the RC low-pass circuits are 1.8 KΩ.
- Also select values for the feedback resistors to get a Butterworth response.

Both stages must have the same $f_c$. Assuming equal-value capacitors,

$$f_c = \frac{1}{2\pi RC}$$

$$C = \frac{1}{2\pi Rf_c} = \frac{1}{2\pi(1.8 \text{ kΩ})(2680 \text{ Hz})} = 0.033 \mu\text{F}$$

Also select $R_2 = R_4 = 1.8 \text{ kΩ}$ for simplicity. Refer to Table 15–1. For a Butterworth response in the first stage, $DF = 1.848$ and $R_1/R_2 = 0.152$. Therefore,

$$R_1 = 0.152R_2 = 0.152(1800 \text{ Ω}) = 274 \text{ Ω}$$

Choose $R_1 = 270 \text{ Ω}$.

In the second stage, $DF = 0.765$ and $R_3/R_4 = 1.235$. Therefore,

$$R_3 = 1.235R_4 = 1.235(1800 \text{ Ω}) = 2.22 \text{ kΩ}$$

Choose $R_3 = 2.2 \text{ kΩ}$.
Active Filters – High-Pass Filters

RC High-pass filter

\[ A_v = \left(1 + \frac{R_F}{R_G}\right) \]

\[ f_{0H} = \frac{1}{2 \pi R_1 C_1} \]
Active Filters – High-Pass Filters

\[ \frac{V_o}{V_1} \]

-20 dB/decade

-40 dB/decade

\[ f_{OL} \]
The Sallen-Key High-Pass Filter

- Components $R_A$, $C_A$, $R_B$ and $C_B$ form the two-pole frequency-selective circuit
- Note that the positions of the resistors and capacitors in the frequency-selective circuit are opposite to those in the low-pass configuration
- As with the other filters, the response characteristic can be optimized by proper selection of the feedback resistors, $R_1$ and $R_2$. 

Active Filters – High-Pass Filters
Active Filters – High-Pass Filters

Cascading High-Pass Filters
Active Filters – Band-Pass Filters

[Diagram of band-pass filter circuit with op-amps, resistors, capacitors, and frequency response graph showing 20 dB/decade gain at mid-frequency and -20 dB/decade attenuation at high and low frequencies, marked as $f_{OL}$ and $f_{OH}$]
Active Filters – Band-Pass Filters

Two-pole high-pass

\[ f_{c1} = \frac{1}{2\pi \sqrt{R_{A1} R_{B1} C_{A1} C_{B1}}} \]
\[ f_{c2} = \frac{1}{2\pi \sqrt{R_{A2} R_{B2} C_{A2} C_{B2}}} \]
\[ f_0 = \sqrt{f_{c1} f_{c2}} \]
Active Filters – Band-Pass Filters

Multiple-Feedback Band-Pass Filter

- The two feedback paths are through $R_2$ and $C_1$
- $R_1$ and $C_1$ provide low-pass response
- $R_2$ and $C_2$ provide high-pass response
- Maximum gain, $A_0$, occurs at the center frequency
- $Q$ values of less than 10 are typical in this type of filter.

$R_1$ and $R_3$ appear in parallel as viewed from the $C_1$ feedback path (with the $V_{in}$ source replaced by a short).

\[
f_0 = \frac{1}{2\pi \sqrt{(R_1 \parallel R_3)R_2C_1C_2}} \quad \text{Making } C_1 = C_2 = C \text{ yields}
\]

\[
f_0 = \frac{1}{2\pi \sqrt{(R_1 \parallel R_3)R_2C^2}} = \frac{1}{2\pi C \sqrt{(R_1 \parallel R_3)R_2}}
\]

\[
= \frac{1}{2\pi C \sqrt{R_2(R_1 \parallel R_3)}} = \frac{1}{2\pi C \sqrt{\left(\frac{1}{R_2}\right)\left(\frac{1}{R_1R_3/R_1 + R_3}\right)}}
\]

\[
f_0 = \frac{1}{2\pi C \sqrt{\frac{R_1 + R_3}{R_1R_2R_3}}}
\]
A value for the capacitors is chosen and then the three resistor values are calculated to achieve the desired values for $f_0$, $BW$, and $A_0$

- $Q = f_0/BW$
- Resistor values can be found using the following formulas (stated without derivation):

\[
R_1 = \frac{Q}{2\pi f_0 CA_0}
\]
\[
R_2 = \frac{Q}{\pi f_0 C}
\]
\[
R_3 = \frac{Q}{2\pi f_0 C (2Q^2 - A_0)}
\]

- For denominator of the expression above to be positive, $A_0 < 2Q^2$
- => a limitation on gain.
Active Filters

State-Variable Filter

Consists of a summing amplifier and two op-amp integrators

Integrators act as single-pole low-pass filters combined in cascade to form a second-order filter

Although used primarily as a band-pass (BP) filter, it also provides low-pass (LP) and high-pass (HP) outputs
Active Filters – Band-Pass Filters

State-Variable Filter

- At input frequencies below $f_c$, input signal passes through the summing amplifier and integrators and fed back out of phase.
- Thus, the feedback signal and input signal cancel for all frequencies below $f_c$.
- At higher frequencies, feedback signal diminishes, allowing the input to pass through to the band-pass output.
- As a result, BP output peaks sharply at $f_c$.
- Stable Qs up to 100 can be obtained.
- Q is set by the feedback resistors $R_5$ and $R_6$ according to equation:

$$Q = \frac{1}{3} \left( \frac{R_5}{R_6} + 1 \right)$$
Active Filters – Band-Stop Filters

Show how to make a notch (band-stop) filter using the circuit
Active Filters – Band-Stop Filters

Show how to make a notch (band-stop) filter using the circuit.
Active Filters – Band-Pass Filters

State-Variable Filter
Determine the center frequency, Q, and BW for the passband of the filter
Active Filters – Band-Pass Filters

State-Variable Filter
Determine the center frequency, $Q$, and BW for the passband of the filter

For each integrator

\[ f_c = \frac{1}{2\pi R_4 C_1} = \frac{1}{2\pi R_7 C_2} f_c \]
\[ = \frac{1}{2\pi(1.0\,\text{k}\Omega)(0.22\,\mu\text{F})} = 7.23\,\text{kHz} \]

\[ f_0 = f_c = 7.23\,\text{kHz} \]

\[ Q = \frac{1}{3} \left( \frac{R_5}{R_6} + 1 \right) = \frac{1}{3} \left( \frac{100\,\text{k}\Omega}{1.0\,\text{k}\Omega} + 1 \right) \]
\[ = 33.7 \]

\[ BW = \frac{f_0}{Q} = \frac{7.23\,\text{kHz}}{33.7} = 215\,\text{Hz} \]
One important application of this filter is minimizing the 50 Hz “hum” in audio systems by setting the center frequency to 50 Hz.
Active Filters – Band-Stop Filters

State-Variable Band-Stop Filter

Verify that the band-stop filter in the figure has a center frequency of 60 Hz, and optimize the filter for a $Q$ of 10.
State-Variable Band-Stop Filter

Verify that the band-stop filter in figure has a center frequency of 60 Hz, and optimize the filter for a \( Q \) of 10

For each integrator

\[
 f_c = f_0 = \frac{1}{2\pi R_4 C_1} = \frac{1}{2\pi R_7 C_2} f_c \\
= \frac{1}{2\pi (12k\Omega)(0.22 \mu F)} = 60 \text{ Hz}
\]

\[
 Q = \frac{1}{3} \left( \frac{R_5}{R_6} + 1 \right) \\
R_5 = (3Q - 1)R_6 \\
\text{Choose } R_6 = 3.3 k\Omega \\
R_5 = [3(10) - 1]3.3k\Omega \\
= 95.7 k\Omega
\]
Optimize the state-variable filter for $Q=50$.
What bandwidth is achieved?
Optimize the state-variable filter for $Q=50$. What bandwidth is achieved?

\[ Q = \frac{1}{3} \left( \frac{R_5}{R_6} + 1 \right) \]

Select $R_6 = 10 \text{ k}\Omega$.

\[ Q = \frac{R_5}{3R_6} + \frac{1}{3} = \frac{R_5 + R_6}{3R_6} \]

\[ 3R_6Q = R_5 + R_6 \]

\[ R_5 = 3R_6Q - R_6 \]

\[ = 3(10 \text{ k}\Omega)(50) - 10 \text{ k}\Omega \]

\[ = 1500 \text{ k}\Omega - 10 \text{ k}\Omega = 1490 \text{ k}\Omega \]

\[ f_0 = \frac{1}{2\pi(12 \text{ k}\Omega)(0.01 \mu\text{F})} = 1.33 \text{ kHz} \]

\[ BW = \frac{f_0}{Q} = \frac{1.33 \text{ kHz}}{50} = 26.6 \text{ Hz} \]
Modify the band-stop filter for a center frequency of 120 Hz
Active Filters – Band-Stop Filters

Modify the band-stop filter for a center frequency of 120 Hz

\[ f_0 = f_c = \frac{1}{2\pi RC} \]

Let \( C \) remain 0.01 \( \mu F \).

\[ R = \frac{1}{2\pi f_0 C} = \frac{1}{2\pi (120 \text{ Hz})(0.01 \mu \text{F})} = \text{133 k}\Omega \]

Change \( R \) in the integrators from 12 k\Omega to 133 k\Omega.
Active Filters – Band-Stop Filters

State-Variable Band-Stop Filter

Find typical resistor and capacitor values for a center frequency of 50 Hz.

<table>
<thead>
<tr>
<th>Standard Resistor Values (±5%)</th>
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<th>100</th>
<th>1.0K</th>
<th>10K</th>
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Electrolytic Capacitor Values Chart

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