DESIGN IDEAS

Sharp Gain Roll-Offs Using the LTC1562 Quad Operational Filter IC (Part 3)

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This is the third in series of articles describing applications of the LTC1562 quad Operational Filter™ IC connected as a lowpass, highpass, notch or bandpass filter with added stopband notches to increase selectivity.

Parts 1 and 2 of the series (Linear Technology VIII: 2, May 1998, pp. 28–31 and IX: 1, February 1999, pp. 31–35) described two notch techniques referred to as “feedforward.” In these techniques, the filter topology was modified to introduce summing junctions in the signal path and passive components were carefully selected to allow summed signals to cancel each other at specific frequencies.

Part 3 of this series describes a new notch technique, the RC notch, that can be broadly applied to create notches at any frequency. At the end of this series of articles, the RC notch technique will be compared to the feedforward schemes and their respective merits and drawbacks will be discussed.

The principle of the RC notch technique is shown in Figure 1, where one 2nd order section of the LTC1562 is connected as a basic all-pole 2nd order lowpass/bandpass filter and its two outputs are summed directly into the next section by means of resistor \( R_{IN2} \) and capacitor \( C_{IN2} \).

Note that, as \( V_{2B} \) is the integral of \( V_{1B} \), the lowpass output \( V_{2B} \) lags the bandpass output \( V_{1B} \) by 90 degrees or, conversely, \( V_{1B} \) leads \( V_{2B} \) by the same amount. Furthermore, as capacitor \( C_{IN2} \) adds another 90 degrees of phase lead to the current \( I_{BP(S)} \), the two AC currents \( I_{BP(S)} \) and \( I_{LP(S)} \) will always be 180 degrees out of phase. It is quite trivial to show that a discrete frequency will always exist where the magnitude of these two currents will be equal and a notch will be formed.

The frequency of the notch can be easily derived by equating the magnitude of the two currents \( I_{LP(S)} \) and \( I_{BP(S)} \), Figure 1; that is: \( I_{LP(S)} = I_{BP(S)} \)

or \( \frac{V_{2B}(s)}{R_{IN2}} = V_{1B}(s)s C_{IN2} \) \( (1) \),

with \( V_{2B}(s) = V_{1B}(1/(sR1C)) \); \( (2) \);

\( R1 = 10k \), \( C = 159.15\mu F \), and \( s = j\omega \)

Substituting (2) into (1) and solving for \( \omega = \omega_{\text{notch}} = \frac{1}{\sqrt{(R_{IN2} \cdot C_{IN2} \cdot R1 \cdot C)}} \) \( (3) \)

Equation 3 above can be rewritten as a function of the center frequency, \( f_{O1} \), of the 2nd order filter section from which it was derived:

\( f_{notch} = f_{O1} \cdot \sqrt{R_{21} \cdot C/(R_{IN2} \cdot C_{IN2})} \) \( (4) \)

Equation (4) allows a quick estimate of the notch frequency relative to the \( f_{O} \). The magnitude \( R_{21} \cdot C \) relative to \( R_{IN2} \cdot C_{IN2} \) will determine whether the notch frequency is higher than, equal to, or lower than the

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**Figure 1.** Summing the BP output (V1A) and the lowpass output (V1B) into the inverting node of the next LTC1562 section to form an RC notch
center frequency, \( f_0 \), of the filter section from which it was derived.

The technique of Figure 1 can be expanded to create high order filters with stopband notches. This is shown in Figure 2, where all four sections of an LTC1562 are used to create an 8th order filter. The notches, as in Figure 1, are formed by summing the two voltage outputs (\( V_{2i}, V_{1i} \)) via (\( R_{INi}, C_{INi} \)), respectively into the inverting node of the following section. As shown, Figure 2 supports three notches. A fourth notch can also be produced if the \( V_{2D}, V_{1D} \) outputs are summed into the inverting input of an external op amp.

If the filter output in Figure 2 is taken from node \( V_{2D} \) and if the frequencies of all the notches are higher than the highest center frequency of any of the cascaded 2nd order sections, the overall filter response is a lowpass. As selective lowpass filters are quite popular and relatively easy to design, a lowpass example will be used to illustrate the RC notch technique. More sophisticated examples will be shown in future articles.

For the sake of thoroughness, the transfer function of Figure 2 is shown below:

\[
G(s) = H \cdot \frac{\prod_{i=1}^{3} (s^2 + \omega_{in}^2) \omega_{o4}^2}{\prod_{i=1}^{3} (s^2 + s\omega_{o4}/\alpha_i + \omega_{o4}^2)}
\]

(5)

where \( H = (R_{24}/R_{IN1}) \cdot (C_{IN2} \cdot C_{IN3} \cdot C_{IN4}/C^3) \)

(6)

and where \( C \) is the internal integrator capacitor.

The DC gain of the filter is the product of the DC gains of the cascaded 2nd order sections and can be written by inspection:

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{R_{24}/R_{IN4}}{R_{23}/R_{IN3}} \cdot \frac{R_{22} \cdot R_{IN2}}{R_{21}/R_{IN1}}
\]

(7)

**An Example, Using Linear Technology FilterCAD™ for Windows®**

Design a lowpass filter with a 100kHz passband and 80dB or more attenuation at 200kHz. The passband gain should be 0dB and the passband ripple should not exceed 0.2db. Use FilterCAD to synthesize the filter.

Table 1 illustrates the first try, with FilterCAD indicating a classical 7th order lowpass elliptic filter. The filter can be realized by cascading three out of four sections of the LTC1562 (Figure 3), where an external op amp is used to realize the third notch. Note the cascading sequence of 2nd order sections illustrated in Figure 3. The unused fourth section of the LTC1562 could perform another filter function, which could be independent from the above lowpass filter design.

The following step-by-step procedure shows how to calculate the external passive components of Figure 3.

1. From the LTC1562 data sheet, calculate all the \( R_{2i} \)s and \( R_{Qi} \)s:

\[
R_{2i} = \frac{(100kHz/f_{oi})^2}{10k}; R_{Qi} = Q_i \cdot \sqrt{(10k \cdot R_{2i})}
\]

\((i = 1, 2, 3 \ldots)\)

\[
R_{21} = 17.37k; R_{22} = 10.387k; R_{23} = 8.176k; R_{Q1} = 9.62k; R_{Q2} = 15.846k; R_{Q3} = 49.087k
\]

2. Calculate resistors \( R_{INi} \) and capacitors \( C_{INi} \).

\( R_{INi} \) should be chosen independently from \( C_{INi} \) by considering DC gains; \( C_{INi} \) will be calculated to make the time constant \( R_{INi} \cdot C_{INi} \) yield the appropriate notch frequency. As there are fewer commercially available capacitor values than resistors, the theoretical value of \( C_{INi} \) will be rounded.
off to its closest commercially available value; \( R_{\text{IN}} \) will then be appropriately adjusted to maintain the required value of the time constant \( R_{\text{IN}} \cdot C_{\text{IN}} \). This algorithm is summarized below.

Set \( R_{\text{IN}} \); Calculate \( C_{\text{IN}} \) from the notch expression (3) or (4); Round off the theoretical value of \( C_{\text{IN}} \) to the closest commercially available value; recalculate \( R_{\text{IN}} \) so that \((R_{\text{IN}} \cdot C_{\text{IN}})_{\text{theoretical}} = (R_{\text{IN}} \cdot C_{\text{IN}})_{\text{commercially obtainable}}\).

Optimally setting \( R_{\text{IN}} \) resistors is easier said than done. One straightforward method would allow unity DC gain at each cascaded stage, that is \( R_{\text{IN}} = R_2 \). This could work if the filter is realized from medium Q stages (for example, Qs less than 1), but for Qs much higher than 0.707, the maximum AC gain of a lowpass 2nd order section is approximately \( (Q \cdot \text{DC gain}) \); an internal node could have much higher gain than the filter output. This could cause internal clipping that could limit the filter’s dynamic range.

A computer program can also be written to calculate the AC gain at each internal node and then make a wise choice for \( R_{\text{IN}} \) resistors. Filter-CAD for Windows already performs this function for the switched capacitor products (LTC1060, LTC1061, LTC1064, LTC1067, LTC1068) and, in the near future, it will also support LTC’s newer RC active products (LTC1562, et al.).

For the purpose of this article, we will use a simple rule of thumb that works fairly well, at least for lowpass elliptic filters: For Qs less than 2, set the DC gain of the second order section equal to unity, for Qs higher than 2 and less than 5, set the DC gain equal to 0.5V/V and for Qs higher than 5 and less than 8, set the DC gain equal to 0.35V/V.

2a: Set: \( R_{\text{IN1}} = R_{21} = 17.37k \); this sets the DC gain of the lowpass node V21 of the first stage to 0dB.

2b: Set: \( R_{\text{IN2}} = R_{22} = 10.387k \); this sets the DC gain of the lowpass node V22 with respect to V21 equal to 0dB. The AC gain at V22 will peak at approximately the center frequency, \( f_{02} \), and the magnitude of the peak will be approximately Q2 times the DC gain. The gain at V22 with respect to \( V_{\text{IN}} \), however, will still be close to 0dB.

Solve for \( C_{\text{IN2}} \) by using (4) above:

\[
C_{\text{IN2}} = \frac{(R_{21} \cdot C)}{(R_{\text{IN2}})} \cdot \left(\frac{f_{01}}{f_{N1}}\right)^2 = 36.655\text{pF}
\]

Choose \( C_{\text{IN2}} = 39\text{pF} \) (standard capacitor value) and readjust the value of \( R_{\text{IN2}} \), such that:

\[
R_{\text{IN2(REAL)}} = \frac{(36.655\text{pF}/39\text{pF}) \cdot (10.387k)} = 9.762k
\]

2c: Set \( R_{\text{IN3}} = 2 \cdot R_{23} = 16.352k \) and calculate \( C_{\text{IN3}} \) from (9) above:

\[
C_{\text{IN3}} = \frac{(R_{22} \cdot C)}{(R_{\text{IN3}})} \cdot \left(\frac{f_{02}}{f_{N2}}\right)^2 = 15.695\text{pF}
\]

Choose \( C_{\text{IN3}} = 15\text{pF} \) (standard capacitor value) and readjust the value of \( R_{\text{IN3}} \) as above (10).

\[
R_{\text{IN3(REAL)}} = \frac{(15.695\text{pF}/15\text{pF}) \cdot (16.352k)} = 17.1k
\]

2d: Calculate the last stage (external op amp) passive components: \( C_{\text{RP}}, R_G, R_{\text{IN4}} \) and \( C_{\text{IN4}} \).

This is slightly more cumbersome than the previous calculations but the simple algorithm outlined below will make this task quite intuitive:

Calculate the desired ratio of \( R_G/R_{\text{IN4}} \) by considering the overall DC gain of the lowpass filter. Start with an arbitrary, yet reasonable, value for \( R_G \), calculate \( R_{\text{IN4}} \) and also calculate \( C_{\text{RP}} \) to realize the 7th pole (real pole) of the filter (see Table 1). Make sure that the value of \( R_{\text{IN4}} \) is not too small (it should be greater than 2k). Adjust the value of \( R_G \) to accommodate a commercially available capacitor, \( C_{\text{RP}} \).

![Diagram](image-url)
Set the overall gain of the filter to its original value.

2d-2. Start with an arbitrary, yet reasonable value, for example RG = 20k, and solve for CRP to obtain the 7th real pole frequency of 61.332kHz.

The choice of capacitors will most likely alter the original ratio of RG/RIN4, so readjust the value of the input resistor RIN1 to restore the DC gain of the filter to its original value.

2d-3. Calculate CIN4 as in the previous steps and adjust the value of RG/RIN4:

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{R_{\text{G}}}{R_{\text{IN4}}} = \frac{R_{\text{G}}}{R_{\text{IN4}}} \cdot \frac{R_{22}}{R_{21}} \cdot \frac{R_{Q2}}{R_{Q1}} = 1V/V \] (11)

2d-4. As the new ratio \(\frac{R_{G}}{R_{\text{IN4}}}\) has changed slightly, adjust RIN1 to reestablish 0dB of DC gain: \[R_{\text{IN1(REAL)}} = 17.37k \cdot \frac{1.9656}{2.06} = 16.36k\]

The new LT1719 comparator can easily be used to create a low power, high performance, sine wave to square wave converter. The fast, 4.5ns delay barely changes with input amplitude fluctuations. The delay is particularly flat, for excellent AM rejection, from –5dBm to 10dBm.

**Conclusion**

The new LT1719 comparator can easily be used to create a low power, high performance, sine wave to square wave converter. The fast, 4.5ns delay barely changes with input amplitude fluctuations. The delay is particularly flat, for excellent AM rejection, from –5dBm to 10dBm.

At frequencies higher than 10MHz, attention to detail in the physical construction of circuits becomes particularly important. With a poor layout, the output toggle action can capacitively or inductively couple back to the input signal, causing distortion. This must be avoided in order to measure the actual performance of the comparator. The LT1719 pinout has been optimized to shield the input signals from the digital signals with two intervening power supply pins.

**Experimental Results**

The resistor values derived above are first rounded off to their nearest 1% values, as shown below:

1% surface mount resistors, type 0805:

\[R_{\text{IN1}} = 18.2k, R_{21} = 17.4k, R_{Q2} = 9.53k, R_{Q3} = 15.8k, R_{\text{IN3}} = 16.9k, R_{\text{IN4}} = 10.5k, R_{Q3} = 21.5k\]

0.15dB and the total output RMS noise is 60µVRMS. With a dual 5V supply, the filter can easily provide a 5V peak-to-peak signal with a 90dB signal-to-noise ratio and better than 0.01% distortion. The attenuation of the filter remains below 80dB for input frequencies up to 6MHz.

**Conclusion**

A simple method of how to systematically synthesize and design a high performance lowpass elliptic filter is fully illustrated above. The experimental results match the theoretical calculations provided; the Q-setting resistors are slightly adjusted to account for the small Q errors of the LTC1562A.