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: $I_{LP(S)} = I_{BP(S)}$

$$\text{or } V_{2B}(s)/R_{IN2} = V_{1B}(s)s\,C_{IN2} \qquad (1),$$

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

$R1 = 10k$, $C = 159.15pF$, and $s = j\omega$

Substituting (2) into (1) and solving for $\omega = \omega(\text{notch}) =$

$$1/\sqrt{(R_{IN2} \bullet C_{IN2} \bullet R1 \bullet C)} \qquad (3)$$

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:

$$f_{01} = 1/(2\pi C\sqrt{R1 \bullet R2})$$

$$f_{(NOTCH)} = f_N = f_{01} \bullet \sqrt{(R21 \bullet C)/(R_{IN2} \bullet C_{IN2})} \qquad (4)$$

Equation (4) allows a quick estimate of the notch frequency relative to the f_O. The magnitude $R21 \bullet C$ relative to $R_{IN2} \bullet C_{IN2}$ will determine whether the notch frequency is higher than, equal to, or lower than the

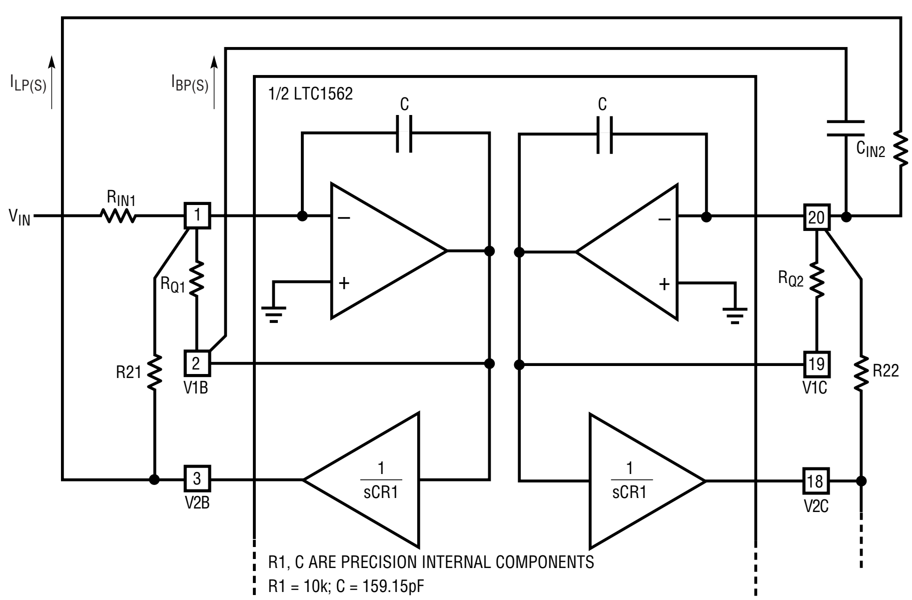


Figure 1. Summing the BP output (V1A) and the lowpass output (V1B) into the inverting node of the next LTC1562 section to form an RC notch

center frequency, f_O, 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 ($V2i$, $V1i$) 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.

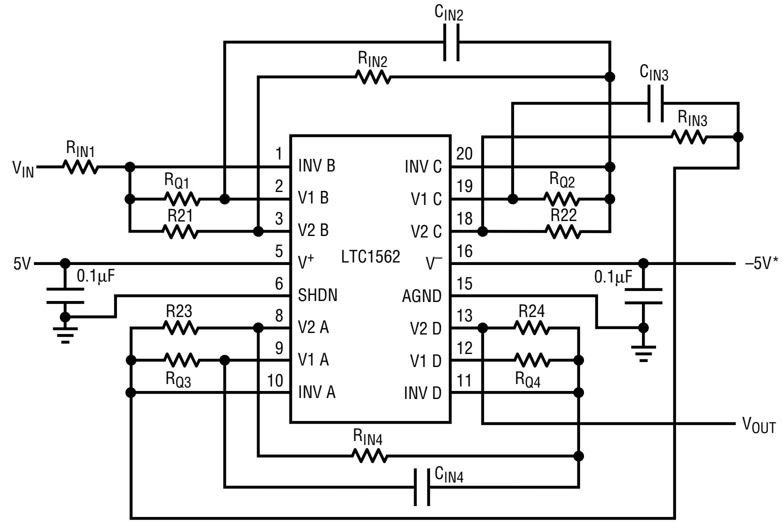
If the filter output in Figure 2 is taken from node V_{2D} and if the frequencies of all the notches are higher than the highest center frequency of any of the cascaded 2nd order sections, the overall filter response is a lowpass. As selective lowpass filters are quite popular and relatively easy to 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:

$$G(s) = H \bullet \frac{\prod^{3} (s^2 + \omega^2_{Ni})\, \omega^2_{04}}{\prod^{3} (s^2 + s\omega_{0i}\alpha_i + \omega^2_{0i})} \quad (5)$$

where $H = (R24/R_{IN1}) \bullet (C_{IN2} \bullet C_{IN3} \bullet C_{IN4})/C^3)$ (6)

and where C is the internal integrator capacitor.



*V– ALSO AT PINS 4, 7, 14 AND 17

Figure 2. Cascading all four sections of an LTC1562 to form an 8th order response with three notches

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:

$$(V_{OUT}/V_{IN}) = (R24/R_{IN4}) \bullet (R23/R_{IN3}) \bullet (R22 \bullet R_{IN2}) \bullet (R21/R_{IN1}) \quad (7)$$

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.

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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:

$$R_{2i} = (100kHz/f_{0i})^2 \bullet 10k;\ R_{Qi} = Q_i \bullet \sqrt{(10k \bullet R_{2i})} \quad (8)$$
$(i = 1, 2, 3 \ldots)$

R21 = 17.37k; R22 = 10.387k;
R23 = 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 $R_{INi} \bullet C_{INi}$ yield the appropriate notch frequency. As there are fewer commercially available capacitor values than resistors, the theoretical value of C_{INi} will be rounded

Table 1. FilterCAD synthesis of classical 7th order elliptic response

Filter Response: Elliptic			Passband Ripple:	0.010dB
Filter Type: Lowpass			Stopband Attenuation:	80.000dB
Order: 7			Passband Frequency:	100.000kHz
			Stopband Frequency:	200.000kHz
f_0	Q	f_N	Q_N	Type
61.3323e3	——	——	——	LP1
75.8750e3	0.7297	204.4515e3	——	LPN
98.1197e3	1.5548	249.0337e3	——	LPN
110.5908e3	5.4287	435.4434e3	——	LPN

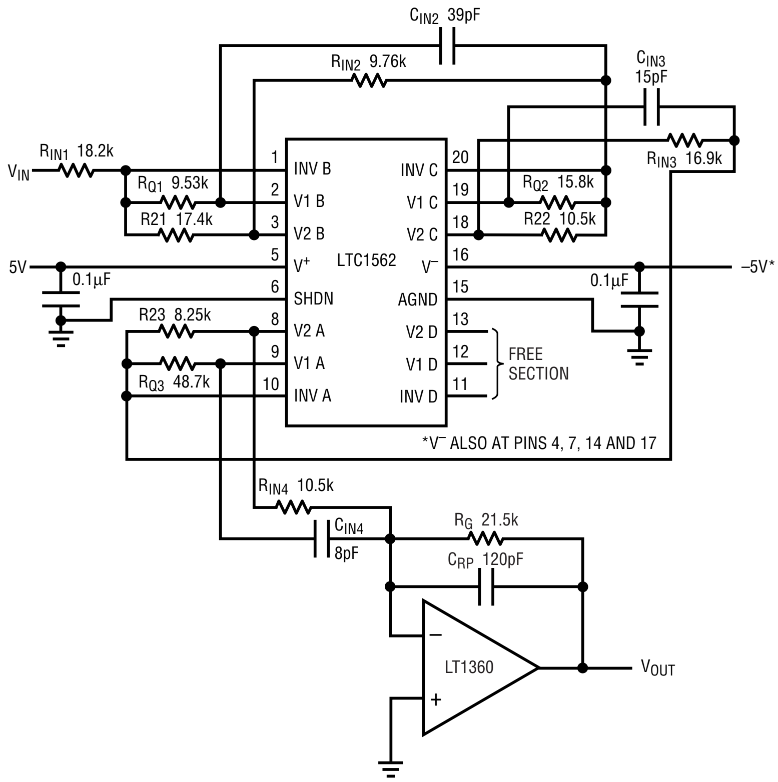

Figure 3. Cascading three sections of an LTC1562 to form a 7th order lowpass elliptic response

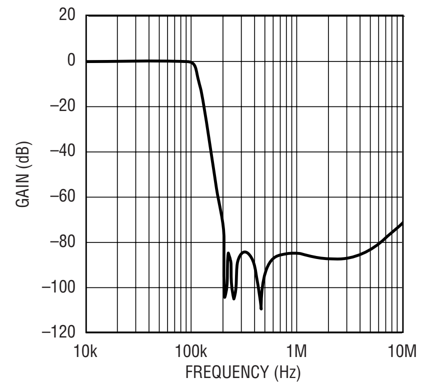

Figure 4. Measured gain response of Figure 2's circuit

off to its closest commercially available value; R_{INi} will then be appropriately adjusted to maintain the required value of the time constant $R_{INi} \bullet C_{INi}$. This algorithm is summarized below.

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

Optimally setting R_{INi} resistors is easier said than done. One straightforward method would allow unity DC gain at each cascaded stage, that is $R_{INi} = R_{2i}$. 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 • 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_{INi} resistors. FilterCAD 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_{IN1} = R21 = 17.37k; this sets the DC gain of the lowpass node V21 of the first stage to 0dB.

2b: Set: R_{IN2} = R22 = 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_{O2}, and the magnitude of the peak will be approximately Q2 times the DC gain. The gain at V22 with respect to V_{IN}, however, will still be close to 0dB.

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

$$C_{IN2} = ((R21 \bullet C)/(R_{IN2})) \bullet (f_{O1}/f_{N1})^2 = 36.655pF \quad (9)$$

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

$$R_{IN2(REAL)} = (36.655pF/39pF) \bullet (10.387k) = 9.762k \quad (10)$$

2c: Set R_{IN3} = 2 • R23 = 16.352k and calculate C_{IN3} from (9) above: $C_{IN3} = ((R22 \bullet C)/R_{IN3}) \bullet (f_{O2}/f_{N2})^2$ = 15.695pF

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

$R_{IN3(REAL)}$ = (15.695pF/15pF) • (16.352k) = 17.1k

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

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LTC1562 notches, continued from page 33

Calculate C_{IN4} as in the previous steps and adjust the value of R_{IN4}. The choice of capacitors will most likely alter the original ratio of R_G/R_{IN4}, so readjust the value of the input resistor R_{IN1} to restore the DC gain of the filer to its original value.

2d-1. Set the overall gain of the lowpass filter to its desired value (here we are assuming 1V/V) and calculate the ratio of R_G/R_{IN4}:

$$(V_{OUT}/V_{IN})\ DC = (R_G/R_{IN4}) \bullet (R23/R_{IN3}) \bullet (R22/R_{IN2}) \bullet (R21/R_{IN1}) = 1V/V \quad (11)$$

$R_G/R_{IN4} = 1.9656$

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

C_{RP} = 129.75pF; choose C_{RP} = 120pF and adjust R_G to 21.625k

Solve for $R_{IN4} = R_G/1.956$ = 11.05k

2d-3. Calculate $C_{IN4} = ((R23 \bullet C)/R_{IN4}) \bullet (f_{O3}/f_{N3})^2$ = 7.595pF

Choose C_{IN4} = 8pF (standard value) and readjust R_{IN4} to

$R_{IN4(REAL)}$ = (7.595pF/8pF) • (11.05k) = 10.49k

2d-4 As the new ratio (R_G/R_{IN4}) has changed slightly [$(R_G/R_{IN4})_{REAL}$ = 2.06 instead of 1.9656], adjust R_{IN1} to reestablish 0dB of DC gain: $R_{IN1(REAL)}$ = 17.37k • (2.06/1.9656) = 18.2k.

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_{IN1} = 18.2k, R21 = 17.4k, R_{Q1} = 9.53k
R_{IN2} = 9.76k, R22 = 10.5k, R_{Q2} = 15.8k
R_{IN3} = 16.9k, R23 = 8.25k, R_{Q3} = 48.7k
R_{IN4} = 10.5k, R_G = 21.5k

The choice of the above 1% values increases the DC gain by 0.24dB so the value of R_{IN1} is raised from 18.2k to 18.7k (1%) to restore the 0dB value of the passband gain.

Resistors R_{Q2} and R_{Q3} are also slightly changed to predistort the values of Q2 and Q3, as shown in the LTC1562 data sheet curve (Q error vs nominal f_O). This is done by lowering the values of R_{Q2} and R_{Q3} by the same percentages as the Q error. The new values are R_{Q2} = 15k (1%) and R_{Q3} = 45.3k (1%).

The filter of Figure 2 was constructed with the resistor values shown above and with 5% type X7R surface mount capacitors:

C_{IN2} = 39pF, C_{IN3} = 15pF, C_{IN4} = 8pF, C_{RP} = 120pF

The active devices are the LTC1562A and the LT1360 op amp. Figure 4 shows the filter gain response. The measured passband error is 0.15dB and the total output RMS noise is 60µV_{RMS}. 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.