ABSTRACT
This application report covers the design of a Sallen-Key bandpass biquad. It gives a design with low component and op amp sensitivities. Then it gives a filter tuning method to compensate for parasitics. A design example illustrates these methods. These biquads are also called KRC or VCVS [voltage-controlled, voltage-source].

Contents
1 Introduction .................................................................................................................. 2
2 Filter Tuning Overview ................................................................................................ 2
3 KRC Bandpass Biquad Design .................................................................................. 2
4 KRC Bandpass Biquad Tuning Method ....................................................................... 5
5 Design Example ........................................................................................................ 5
6 SPICE Models ........................................................................................................... 9
7 Summary ................................................................................................................... 9
8 References ................................................................................................................ 10
Appendix A Estimating the Sensitivity Matrix ............................................................... 11

List of Figures
1 Bandpass Biquad ........................................................................................................ 3
2 Bandpass Filter ........................................................................................................... 5
3 Simulated Filter Magnitude Response ....................................................................... 8
4 Simulated Filter Magnitude Response ....................................................................... 9
1 Introduction

Changes in component values over process, environment and time affect the performance of a filter. To achieve a greater production yield, the filter needs to be insensitive to these changes. This application report presents a design algorithm that results in low sensitivity to component variation. For information on evaluating the sensitivity performance of your filter, see [6].

To achieve the best production yield, the nominal filter design must also compensate for component and board parasitics. This document gives a method to empirically tune your filter. For the background theory, see [5], [7].

2 Filter Tuning Overview

This section shows a simple tuning method that compensates for the parasitic elements in your filter.

To minimize the impact of parasitics:
- Keep signal paths as short as possible
- Minimize the length of all feedback loops
- Use components with small parasitics
- Use good PCB layout techniques
- Use an op amp with adequate bandwidth ($f_{3\,\text{dB}}$) and slew rate (SR):
  - $f_{3\,\text{dB}} \geq 10 \times f_H$
  - $\text{SR} > 5 \times f_H \times V_{\text{PEAK}}$
  - where $f_H$ is the highest frequency in the passband of the filter, and $V_{\text{PEAK}}$ is the largest peak voltage.
  - Make sure the op amp is stable at the chosen gain.

To compensate for the parasitic elements:
1. Start with a low sensitivity, low parasitic design
2. Calculate the sensitivities of the filter response parameters to the resistors and capacitors [6]
3. Measure the filter’s response. The important parameters to extract are:
   - Maximum passband gain ($H_p$)
   - Pole frequency ($\omega_p$)
   - Pole quality ($Q_p$)
     - The Design Example section gives a simple extraction method. Use accurate component values for the prototype filter so that the nominal design point will be near the center of the possible component values
4. Use the information in steps 2 and 3 to adjust the resistor and capacitor values:
   - Set up the linear equations relating the relative change in filter response parameters ($\Delta H_p/H_p$, $\Delta \omega_p/\omega_p$ and $\Delta Q_p/Q_p$) to the relative change in the components to be adjusted
   - The number of components to change is the same as the number of filter response parameters
   - The coefficients of these linear equations are the component sensitivities [6]
   - Solve for the relative change in component values
   - Calculate the new component values
5. Repeat steps 3 and 4 until the nominal response is close enough to the desired response.

3 KRC Bandpass Biquad Design

The biquad shown in Figure 1 is a Sallen-Key bandpass biquad. $V_{\text{in}}$ needs to be a voltage source with low output impedance.
Figure 1. Bandpass Biquad

$R_2$ attenuates the input signal for low gains. $V_{IN}$, $R_1$ and $R_2$ can be replaced with their Thévenin equivalent voltage ($\alpha V_{IN}$) and impedance ($R_{12}$):

$$\alpha = \frac{R_2}{R_1 + R_2}$$

$$R_{12} = R_1 \parallel R_2$$

The transfer function is:

$$\frac{V_0}{V_{IN}} \approx \frac{H_p (\alpha_p / Q_p) s}{s^2 + (\alpha_p / Q_p) s + (\alpha_p^2)}, \quad s = j\omega$$

(1)

where:

$$\alpha_p = \left( \frac{1}{R_{12}} + \frac{1}{R_4} - \frac{K - 1}{R_5} \right) + \frac{1}{R_2} + \frac{1}{R_4 C_3}$$

$$\alpha_p^2 = \frac{1}{R_4 C_2 C_3} \left( \frac{1}{R_{12}} + \frac{1}{R_5} \right)$$

$$K = \frac{1}{R_2} + \frac{R_4}{R_0}$$

$$H_p = \frac{\alpha K}{R_{12} C_2} \cdot \frac{Q_p}{\alpha_p}$$

(2)

To achieve low sensitivities, use this design algorithm:

1. Use this biquad when: $0.5 \leq Q_p < 5.0$
   Steps 2 and 3 assume this condition to be true.
2. Partition the gain:
   - Use a low noise amplifier before this biquad if you need a large gain
   - Initialize the peak passband gain in 1 of 3 ways:
     - For the best sensitivity performance, use: $H_p = 1.0$
     - For reasonable sensitivity performance and reduced component spreads, use: $H_p = \max\{1.0, Q_p\}$
     - For dynamic range performance, scale $H_p$ as needed. Limit the peak gain to: $H_p < 10.0$
3. Set the input attenuation: $\alpha = \min\{1.0, H_p\}$
4. Initialize one of the resistor spreads ($r^2 = R_{12}/R_4$) and the op amp gain ($K$):
   - $A_1 = 0.0381 Q_p^{-1.51} (H_p/\alpha)^{-1.27}$
   - $A_2 = 0.00206 Q_p^{-1.99} (H_p/\alpha)^{1.39}$
   - $r^2 = \max\{0.1, A_1 + A_2\}$
   - $B_1 = 0.456(\max\{1, Q_p\})^{-1.22} (H_p/\alpha)^{1.22}$
   - $B_2 = 0.0260(\max\{1, Q_p\})^{1.76} (H_p/\alpha)^{-1.51}$
   - $K = 1.0 + \max\{0.1, B_1 + B_2\}$
5. Select an op amp with adequate bandwidth ($f_{3\text{ dB}}$) and slew rate (SR):
   - $f_{3\text{ dB}} \geq 10 f_H$
   - $SR > 5 f_H V_{\text{PEAK}}$
• where \( f_H \) is the highest frequency in the passband, and \( V_{PEAK} \) is the largest peak voltage. Make sure the op amp is stable at a gain of \( A_v = K \).

6. For current-feedback op amps, use the recommended value of \( R_f \) for a gain of \( A_v = K \). For voltage-feedback op amps, select \( R_f \) for noise and distortion performance. Then set \( R_g \) for the correct gain: \( R_g = R_f / (K - 1) \).

7. Calculate the capacitor spread \( \left( \frac{c^2}{C_2/C_3} \right) \), and the other resistor spread \( \left( \frac{\beta^2}{R_12/R_6} \right) \):

\[
\begin{align*}
A_0 &= (K - 1)(\alpha K_0 / H_p)^2 \\
A_1 &= r^2 + K(1 - \alpha / H_p) \\
c^2 &= \frac{1}{r^2} \cdot \frac{2A_0}{A_1 + \sqrt{A_1^2 + 4A_0}} \\
\beta^2 &= \left( \frac{\alpha K_0 / H_p}{\sqrt{c^2 r^2}} \right)^2 \cdot \frac{1}{c^2 r^2} - 1
\end{align*}
\]

8. Initialize the resistance level \( R = \sqrt{R_{12} R_6} \). Increasing \( R \) will:

- Increase the output noise
- Improve the distortion performance
- Improve the isolation between the op amp outputs and \( C_2 \) and \( C_3 \)
- Make the parasitic capacitances a larger fraction of \( C_2 \) and \( C_3 \)

9. Calculate the capacitance level \( C = \sqrt{c^2 C_2 C_3} \)

10. Calculate the resistors and capacitors:

\[
\begin{align*}
R_{12} &= rR \\
R_1 &= R_{12} / \alpha \\
R_2 &= R_{12} / (1 - \alpha) \\
R_3 &= R_{12} / \beta^2 \\
C_2 &= cC \\
C_3 &= C / c
\end{align*}
\]

11. Set the resistors and capacitors to the nearest standard values.

The component sensitivity formulas are in the table below. The sensitivities to \( \alpha = K \) are a measure of this biquad’s sensitivity to the op amp group delay [5]. To evaluate this biquad’s sensitivity performance, see [6]. To manually pre-distort this filter, and compensate for parasitic capacitances, see [5], [7].

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( S_{H_2} )</th>
<th>( S_{H_3} )</th>
<th>( S_{H_4} )</th>
<th>( S_{H_5} )</th>
<th>( S_{H_6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_f )</td>
<td>( \frac{H_p}{K} - 1 )</td>
<td>( -\alpha )</td>
<td>( \frac{S_{H_2}^2 + S_{H_3}^2 + 1}{2(1 + \beta^2)} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R_2 )</td>
<td>( 1 - \alpha ) ( \frac{H_p}{\alpha K} )</td>
<td>( -\frac{1}{2} )</td>
<td>( \frac{S_{H_2}^2 + S_{H_3}^2}{2(1 + \beta^2)} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R_3 )</td>
<td>( (1 + \beta^2) r^2 )</td>
<td>( -\beta^2 )</td>
<td>( \frac{S_{H_2}^2 + S_{H_3}^2}{2(1 + \beta^2)} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_2 )</td>
<td>( -\frac{H_p c^2 r^2}{\alpha K} )</td>
<td>( -\frac{1}{2} )</td>
<td>( \frac{S_{H_2}^2 + S_{H_3}^2 + 1}{2(1 + \beta^2)} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_3 )</td>
<td>( -S_{C_2}^2 )</td>
<td>( -\frac{1}{2} )</td>
<td>( -S_{C_3}^2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R_1 )</td>
<td>( \frac{H_p r^2}{\alpha (\alpha + 1)} \cdot \frac{K - 1}{K} )</td>
<td>( 0 )</td>
<td>( \frac{S_{H_3}^2}{S_{H_5}^2} )</td>
<td>( \frac{S_{H_3}^2}{S_{H_5}^2} - \frac{K - 1}{K} )</td>
<td></td>
</tr>
<tr>
<td>( R_2 )</td>
<td>( -S_{H_1}^2 )</td>
<td>( 0 )</td>
<td>( -S_{H_2}^2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( K )</td>
<td>( 1 )</td>
<td>( 0 )</td>
<td>( H_p r^2 )</td>
<td>( \frac{1}{\alpha} )</td>
<td></td>
</tr>
</tbody>
</table>
KRC Bandpass Biquad Tuning Method

To tune this filter, use this algorithm:

1. Start with a low-sensitivity design.
2. Calculate the sensitivities of $H_p$, $\omega_p$, and $Q_p$ to the components.
3. Set up the linear equations:
   - Choose the 3 components $\alpha_i$ that will be changed to adjust $H_p$, $\omega_p$, and $Q_p$.
   - Create this sensitivity matrix using the formulas (see Appendix A for a simple method that uses measurement or simulation results):
     \[
     M_3 = \begin{bmatrix}
     H_p & H_p & H_p \\
     \omega_p & \omega_p & \omega_p \\
     Q_p & Q_p & Q_p
     \end{bmatrix}
     \]
   - Invert the sensitivity matrix ($M_3^{-1}$).
4. Measure the filter response, and then extract $H_p$, $\omega_p$, and $Q_p$:
   - Find the maximum gain magnitude: $H_p = \max(|H(j\omega)|)$
   - Find the $-3$ dB corner frequencies $f_1$ and $f_2$, where $f_2 > f_1$
     \[
     \omega_p = 2\pi \sqrt{f_1 f_2}
     \]
   - Calculate $\omega_p$ and $Q_p$:
     \[
     Q_p = \sqrt{\frac{f_1}{f_2 - f_1}}
     \]
5. Calculate the needed changes in $H_p$, $\omega_p$, and $Q_p (X)$:
   \[
   \Delta X/X = 1 - X_{\text{meas}}/X_{\text{nom}}
   \]
   where $X_{\text{nom}}$ and $X_{\text{meas}}$ are the nominal and measured values of $X$. Limit the relative changes in $X$:
   \[
   \Delta X/X \leftarrow \max\{-0.5, \min\{1.0, \Delta X/X\}\}
   \]
6. Calculate the needed component values:
   - Estimate the relative changes in $\alpha_i$, and then limit them:
   - Calculate the new $\alpha_i$:
     \[
     \alpha_i \leftarrow \alpha_i (1 + \Delta \alpha_i/\alpha_i)
     \]
   - Change the filter components to these new values; use accurate component values when building the prototype filter so that the nominal design point will be near the center of the possible component values.
7. Repeat steps 4–6 until the nominal response is close enough to the desired response.

5 Design Example

The circuit shown in Figure 2 is a 4th-order bandpass filter. This filter cascades two bandpass biquads: sections A and B. Use a voltage source with low output impedance, such as the CLC111 buffer, for $V_{\text{IN}}$. 

![Figure 2. Bandpass Filter](image-url)

Submit Documentation Feedback

Copyright © 1996–2013, Texas Instruments Incorporated
The nominal filter specifications are:

- \( f_{sL} = 15 \text{ MHz} \) — (lower stopband edge frequency)
- \( f_{sH} = 40 \text{ MHz} \) — (lower passband edge frequency)
- \( f_{uL} = 60 \text{ MHz} \) — (upper passband edge frequency)
- \( f_{uH} = 135 \text{ MHz} \) — (upper stopband edge frequency)
- \( A_p = 3.0 \text{ dB} \) — (maximum passband ripple)
- \( A_s = 30 \text{ dB} \) — (minimum stopband attenuation)
- \( H_p = 0 \text{ dB} \) — (passband voltage gain)

The second-order Butterworth lowpass prototype filter meets these specifications [1] through [4]. The \( H_p \) values shown below give a maximum gain of 1.00 from \( V_{in} \) to each biquad output. The transformed filter is:

<table>
<thead>
<tr>
<th>Section</th>
<th>( A )</th>
<th>( B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_p/2\pi ) [MHz]</td>
<td>42.36</td>
<td>56.65</td>
</tr>
<tr>
<td>( Q_p ) [ ]</td>
<td>3.501</td>
<td>3.501</td>
</tr>
<tr>
<td>( H_p ) [V/V]</td>
<td>1.000</td>
<td>2.043</td>
</tr>
</tbody>
</table>

Overall Design:
1. Restrict the resistor and capacitor ratios to: \( 0.1 \leq c^2, r^2, \beta^2 \leq 10 \)
2. Use 1% resistors (chip metal film, 1206 SMD)
3. Use 5% capacitors (ceramic chip, 1206 SMD)
4. Use standard resistor and capacitor values
5. Use the same \( H_p \) in both sections to simplify the design. Also set the overall gain to
   \( 1.00^{1/H_p} = \sqrt{(1.000)(2.043)} = 1.429 \)

Section A Design:
1. \( Q_p (3.501) \) meets the required limits
2. \( H_p (1.429) \) is between the first two criteria in step 2 of the design algorithm; the sensitivity performance and component spreads should be reasonable
3. Initialize \( \alpha \) to 1.00; \( R_{2A} \) is an open circuit
4. Initialize \( r^2 \) & \( K \):
   - \( A_1 = 0.1606 \) \( A_2 = 0.0003 \)
   - \( r^2 = 0.1609 \)
   - \( B_1 = 0.1528 \) \( B_2 = 0.1376 \)
   - \( K = 1.290 \)
5. The CLC446 is a current-feedback op amp:
   - \( f_{3dB} = 400 \text{ MHz} < 10 f_{uL} = 600 \text{ MHz} \) (\( f_H = f_{uL} \)); the op amp strongly affects the filter
   - \( SR = 2000 \text{ V/µs} \), while a 60 MHz, 2 Vpp sinusoid requires more than 300 V/µs
6. Set \( R_{IA} \) to the CLC446’s recommended \( R_i \) at \( A_v = +1.290 \), then calculate \( R_{gA} \):
   - \( R_{IA} = 392\Omega \)
   - \( R_{gA} = R_{IA}/(K - 1) = 1352\Omega \)
7. Calculate \( c^2 \) and \( \beta^2 \):
   - \( A_0 = 2.897 \) \( A_1 = 0.5482 \)
   - \( c^2 = 9.011 \)
   - \( \beta^2 = 5.889 \)
8. Initialize $R = 300\,\Omega$

9. Calculate $C: \quad C = \frac{\sqrt{1 + 5.889}}{2\pi(42.36\,\text{MHz}) \cdot (300\,\Omega)} = 32.87\,\text{pF}$

10. The initial values are in the table below

Section B Design:

$H_p$ and $Q_p$ are the same as in section A, but $\omega_p$ is different. To change the pole frequency, scale the resistors $R_{1B}$, $R_{4B}$ and $R_{5B}$:

$$R_{xB} \leftarrow R_{xA} \cdot \left(\frac{\omega_{pA}}{\omega_{pB}}\right) = R_{xA} \cdot 0.7477$$

The initial component values are:

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>120</td>
</tr>
<tr>
<td>$R_4$</td>
<td>748</td>
</tr>
<tr>
<td>$R_5$</td>
<td>20.4</td>
</tr>
<tr>
<td>$C_2$</td>
<td>98.7</td>
</tr>
<tr>
<td>$C_3$</td>
<td>11.0</td>
</tr>
<tr>
<td>$R_f$</td>
<td>392</td>
</tr>
<tr>
<td>$R_g$</td>
<td>1352</td>
</tr>
</tbody>
</table>

Filter Tuning:

This section uses simulated results; different layout and component parasitics will change the tuning results. Simulations used the following parasitics:

- 0.2 pF across all resistors
- 1.0 pF to ground at CLC446 non-inverting inputs
- A group delay of 0.56 ns for the CLC446 at 50 MHz, using a good simulation model

1. The sensitivities for sections A and B are equal since they are not functions of $\omega_p$. They are:

<table>
<thead>
<tr>
<th>$\alpha_i$</th>
<th>$H_p$</th>
<th>$\omega_p$</th>
<th>$Q_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>0.11</td>
<td>-0.07</td>
<td>1.04</td>
</tr>
<tr>
<td>$R_4$</td>
<td>1.78</td>
<td>-0.50</td>
<td>1.28</td>
</tr>
<tr>
<td>$R_5$</td>
<td>-1.89</td>
<td>-0.43</td>
<td>-2.32</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-1.61</td>
<td>-0.50</td>
<td>-1.11</td>
</tr>
<tr>
<td>$C_3$</td>
<td>1.61</td>
<td>-0.50</td>
<td>1.11</td>
</tr>
<tr>
<td>$R_f$</td>
<td>2.12</td>
<td>0.00</td>
<td>1.89</td>
</tr>
<tr>
<td>$R_g$</td>
<td>-2.12</td>
<td>0.00</td>
<td>-1.89</td>
</tr>
<tr>
<td>$K$</td>
<td>1.00</td>
<td>0.00</td>
<td>8.42</td>
</tr>
</tbody>
</table>

$$\begin{bmatrix} \Delta R_1 / R_1 \\ \Delta R_4 / R_4 \\ \Delta R_g / R_g \end{bmatrix} = M_3^{-1} \begin{bmatrix} \Delta H_p / H_p \\ \Delta \omega_p / \omega_p \\ \Delta Q_p / Q_p \end{bmatrix}$$

where:

$$M_3 = \begin{bmatrix} 0.11 & 1.78 & -2.12 \\ -0.07 & -0.50 & 0.00 \\ 1.04 & 1.28 & -1.89 \end{bmatrix}$$

$$M_3^{-1} = \begin{bmatrix} -0.91 & -0.62 & 1.02 \\ 0.13 & -1.91 & -0.14 \\ -0.41 & -1.64 & -0.07 \end{bmatrix}$$

2. To tune the filter, change $R_1$, $R_4$ and $R_g$: 

\begin{align*}
\Delta R_1 &= M_3^{-1} \begin{bmatrix} \Delta H_p / H_p \\ \Delta \omega_p / \omega_p \\ \Delta Q_p / Q_p \end{bmatrix} \\
\Delta R_4 &= M_3^{-1} \begin{bmatrix} \Delta H_p / H_p \\ \Delta \omega_p / \omega_p \\ \Delta Q_p / Q_p \end{bmatrix} \\
\Delta R_g &= M_3^{-1} \begin{bmatrix} \Delta H_p / H_p \\ \Delta \omega_p / \omega_p \\ \Delta Q_p / Q_p \end{bmatrix}
\end{align*}
3. The results of tuning section A are:

<table>
<thead>
<tr>
<th>Iteration No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>120</td>
<td>98.7</td>
<td>89.3</td>
<td>90.8</td>
</tr>
<tr>
<td>$R_2$</td>
<td>748</td>
<td>496</td>
<td>488</td>
<td>492</td>
</tr>
<tr>
<td>$R_3$</td>
<td>1352</td>
<td>676</td>
<td>708</td>
<td>700</td>
</tr>
<tr>
<td>$H_p$</td>
<td>0.736</td>
<td>1.625</td>
<td>1.373</td>
<td>1.433</td>
</tr>
<tr>
<td>$\omega_p/2\pi$</td>
<td>34.62</td>
<td>41.76</td>
<td>42.57</td>
<td>42.32</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>2.212</td>
<td>4.226</td>
<td>3.335</td>
<td>3.504</td>
</tr>
<tr>
<td>$\Delta H_p/H_p$</td>
<td>48.5</td>
<td>−13.7</td>
<td>3.92</td>
<td>−0.28</td>
</tr>
<tr>
<td>$\Delta \omega_p/\omega_p$</td>
<td>18.3</td>
<td>1.42</td>
<td>−0.50</td>
<td>0.09</td>
</tr>
<tr>
<td>$\Delta Q_p/Q_p$</td>
<td>36.8</td>
<td>−20.7</td>
<td>4.74</td>
<td>−0.09</td>
</tr>
<tr>
<td>$\Delta R_1/R_1$</td>
<td>−17.9</td>
<td>−9.52</td>
<td>1.58</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta R_4/R_4$</td>
<td>−33.8</td>
<td>−1.59</td>
<td>0.79</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta R_g/R_g$</td>
<td>−50.0</td>
<td>4.75</td>
<td>−1.13</td>
<td>—</td>
</tr>
</tbody>
</table>

4. The results of tuning section B are:

<table>
<thead>
<tr>
<th>Iteration No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>90.0</td>
<td>66.5</td>
<td>62.9</td>
<td>63.3</td>
</tr>
<tr>
<td>$R_2$</td>
<td>559</td>
<td>363</td>
<td>357</td>
<td>360</td>
</tr>
<tr>
<td>$R_3$</td>
<td>1352</td>
<td>740</td>
<td>784</td>
<td>779</td>
</tr>
<tr>
<td>$H_p$</td>
<td>0.993</td>
<td>1.663</td>
<td>1.384</td>
<td>1.428</td>
</tr>
<tr>
<td>$\omega_p/2\pi$</td>
<td>45.66</td>
<td>55.94</td>
<td>56.95</td>
<td>56.62</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>3.029</td>
<td>4.174</td>
<td>3.391</td>
<td>3.496</td>
</tr>
<tr>
<td>$\Delta H_p/H_p$</td>
<td>30.5</td>
<td>−16.4</td>
<td>3.15</td>
<td>0.07</td>
</tr>
<tr>
<td>$\Delta \omega_p/\omega_p$</td>
<td>19.4</td>
<td>1.25</td>
<td>−0.53</td>
<td>0.05</td>
</tr>
<tr>
<td>$\Delta Q_p/Q_p$</td>
<td>13.5</td>
<td>−19.2</td>
<td>3.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$\Delta R_1/R_1$</td>
<td>−26.1</td>
<td>−5.48</td>
<td>0.67</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta R_4/R_4$</td>
<td>−35.0</td>
<td>−1.83</td>
<td>0.98</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta R_g/R_g$</td>
<td>−45.3</td>
<td>6.00</td>
<td>−0.64</td>
<td>—</td>
</tr>
</tbody>
</table>

Figures 3 and 4 show the simulated filter gain. The curve numbers are:
1. The ideal gain
2. The gain for the initial design (Iteration 1)
3. The gain for the tuned filter (Iteration 4)
The final standard component values are:

<table>
<thead>
<tr>
<th>Component</th>
<th>Standard Tuned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Section A</td>
</tr>
<tr>
<td>R₁</td>
<td>[Ω]</td>
</tr>
<tr>
<td>R₄</td>
<td>[Ω]</td>
</tr>
<tr>
<td>R₅</td>
<td>[Ω]</td>
</tr>
<tr>
<td>C₂</td>
<td>[pF]</td>
</tr>
<tr>
<td>C₃</td>
<td>[pF]</td>
</tr>
<tr>
<td>R₇</td>
<td>[Ω]</td>
</tr>
<tr>
<td>R₈</td>
<td>[Ω]</td>
</tr>
</tbody>
</table>

6 **SPICE Models**

SPICE models are available for most of Comlinear’s amplifiers. These models support nominal DC, AC, AC noise and transient simulations at room temperature.

We recommend simulating with Comlinear’s SPICE models to:
- Predict the op amp’s influence on filter response
- Support quicker design cycles

Include board and component parasitic models to obtain a more accurate prediction of the filter’s response.

To verify your simulations, we recommend bread-boarding your circuit.

7 **Summary**

This application report contains an easy to use design algorithm for a low sensitivity, Sallen-Key bandpass biquad. Designing for low $H_p$, $\omega_p$ and $Q_p$ sensitivities gives:
- Reduced filter variation over process, temperature and time
- Higher manufacturing yield
- Lower component cost

A low sensitivity design is not enough to produce high manufacturing yields. This document shows how to tune the filter to compensate for parasitics; no assumptions about the parasitics are necessary. The components must also have low tolerance, small parasitics and low temperature coefficients.
8 References


NOTE: The circuits included in this application report have been tested with National Semiconductor parts that may have been obsoleted and/or replaced with newer products. To find the appropriate replacement part for the obsolete device, see the CLC to LMH Conversion Table (SNOA428).
Appendix A Estimating the Sensitivity Matrix

For filters where the sensitivity formulas are not readily available, this appendix gives a simple method to estimate the entries in the sensitivity matrix.

To estimate the sensitivity matrix entries using measurement or simulation results, use this algorithm:
1. Choose the 3 components \( \alpha \) that will be changed to adjust \( H_p \), \( \omega_p \) and \( Q_p \) (X)
2. Calculate the sensitivities of \( H_p \), \( \omega_p \) and \( Q_p \) to the chosen components:
   - Extract the parameters \( H_p \), \( \omega_p \) and \( Q_p \) at the nominal values of \( \alpha \)
   - Extract the parameters \( H_p \), \( \omega_p \) and \( Q_p \) when only one \( \alpha \) is different from its nominal value; this results in 3 sets of 3 modified performance parameters
   
   \[
   S_X^{\alpha_i} = \frac{\Delta X}{\Delta \alpha_i}, \quad \Delta \alpha_i = \alpha_i - \alpha_{nom} = 0
   \]
   
   \[
   S_X^{\alpha_1} = \frac{\Delta X}{\Delta \alpha_1}, \quad \Delta \alpha_1 = \alpha_1 - \alpha_{nom} = 0
   \]
   
   \[
   S_X^{\alpha_2} = \frac{\Delta X}{\Delta \alpha_2}, \quad \Delta \alpha_2 = \alpha_2 - \alpha_{nom} = 0
   \]
   
   - Estimate the sensitivities (X is \( H_p \), \( \omega_p \) or \( Q_p \)): \[
   M_3 = \begin{bmatrix}
   S_{H_p}^{\alpha_1} & S_{H_p}^{\alpha_2} & S_{H_p}^{\alpha_3} \\
   S_{\omega_p}^{\alpha_1} & S_{\omega_p}^{\alpha_2} & S_{\omega_p}^{\alpha_3} \\
   S_{Q_p}^{\alpha_1} & S_{Q_p}^{\alpha_2} & S_{Q_p}^{\alpha_3}
   \end{bmatrix}
   \]
3. From the sensitivity matrix:
4. Invert the sensitivity matrix \((M_3^{-1})\)

Example:
As an example, suppose that the following measurements result from the 4 conditions in Step 2 (italicized numbers are changed from nominal):

<table>
<thead>
<tr>
<th>Condition No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 )</td>
<td>[Ω]</td>
<td>120</td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td>( R_4 )</td>
<td>[Ω]</td>
<td>748</td>
<td>748</td>
<td>715</td>
</tr>
<tr>
<td>( R_5 )</td>
<td>[Ω]</td>
<td>1352</td>
<td>1352</td>
<td>1352</td>
</tr>
<tr>
<td>( H_p )</td>
<td>[V/V]</td>
<td>0.736</td>
<td>0.729</td>
<td>0.681</td>
</tr>
<tr>
<td>( \omega_p/2\pi )</td>
<td>[MHz]</td>
<td>34.62</td>
<td>34.84</td>
<td>35.51</td>
</tr>
<tr>
<td>( Q_p )</td>
<td></td>
<td>2.212</td>
<td>2.110</td>
<td>2.096</td>
</tr>
</tbody>
</table>

where the Condition # means:
1. Nominal values
2. \( \Delta R_1 \neq 0 \), and \( \Delta R_2 = \Delta R_3 = 0 \)
3. \( \Delta R_2 \neq 0 \), and \( \Delta R_1 = \Delta R_3 = 0 \)
4. \( \Delta R_3 \neq 0 \), and \( \Delta R_1 = \Delta R_2 = 0 \)

The sensitivity of \( H_p \) to \( R_1 \) is estimated as:

\[
S_{H_p}^{R_1} = \frac{0.729 - 0.736}{0.736 - 115/120} \approx 0.23
\]
Estimating the other sensitivities produces these sensitivity matrices:

\[
M_3 \approx \begin{bmatrix}
0.23 & 1.69 & -1.98 \\
-0.15 & -0.58 & 0.06 \\
1.11 & 1.19 & -1.83 \\
\end{bmatrix}
\]

\[
M_3^{-1} \approx \begin{bmatrix}
-0.95 & -0.70 & 1.00 \\
0.20 & -1.70 & -0.27 \\
-0.45 & -1.53 & -0.11 \\
\end{bmatrix}
\]
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

<table>
<thead>
<tr>
<th>Products</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td><a href="http://www.ti.com/audio">www.ti.com/audio</a></td>
</tr>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
</tr>
</tbody>
</table>

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2013, Texas Instruments Incorporated