AN2168 presents the theory behind switched capacitor filters, and provides guidelines and examples for implementing these filters in PSoC 1 devices. Filters discussed include low pass, band pass, high pass, notch, and elliptical. Example projects for each type of filter are provided.

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1 **Introduction**

A filter is a device that passes or rejects certain frequencies of a signal. Four common types of filters are:

- Low pass filter
- Band pass filter
- High pass filter
- Notch filter

All these filters can be built using PSoC switched capacitor blocks. For a better understanding of switched capacitor blocks in general, see Application Note AN2041 "Understanding Switched Capacitor Blocks."

2 **Filter Basics 101**

The basic building block of second order filters is the second order universal filter transfer function. It is defined in Equation 1.

\[
H(s) = \frac{h_{bp}\left(\frac{s}{2\pi f_0}\right)^2 + h_{lp}\left(\frac{s}{2\pi f_0}\right) + h_p}{\left(\frac{s}{2\pi f_0}\right)^2 + d\left(\frac{s}{2\pi f_0}\right) + 1}
\]

Equation 1

Five variables \((h_{bp}, h_{lp}, h_p, d, \text{ and } f_0)\) allow construction of all filters types. The definition of each is given below.
2.1 Roll Off Frequency ($f_0$)
This is the frequency where the “s” terms start to dominate. Frequencies below these values are considered “low,” above this value are considered “high,” and around this value are considered in “band.”

2.1.1 Damping ($d$)
Damping is a measure of how a filter transitions from lower frequencies to higher frequencies. It is an index of the filter’s tendency to oscillate. Practical damping values range from 0 to 2. Table 1 shows the performance for different damping values.

<table>
<thead>
<tr>
<th>Damping Value</th>
<th>Filter Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d &lt; 0$</td>
<td>Unstable</td>
</tr>
<tr>
<td>$d = 0$</td>
<td>Oscillator</td>
</tr>
<tr>
<td>$d = 1.414$</td>
<td>Critically damped</td>
</tr>
<tr>
<td>$d = 2$</td>
<td>Fully damped</td>
</tr>
<tr>
<td>$d &gt; 2$</td>
<td>Excessively damped</td>
</tr>
</tbody>
</table>

2.1.2 High Pass Coefficient ($h_{hp}$)
This is the coefficient of the numerator that dominates for frequencies greater than $f_0$.

2.1.3 Band Pass Coefficient ($h_{bp}$)
This is the coefficient of the numerator that dominates for frequencies near $f_0$.

2.1.4 Low Pass Coefficient ($h_{lp}$)
This is the coefficient of the numerator that dominates for frequencies lower than $f_0$.

These second order filter stages can be cascaded to produce higher order filters. Use the spreadsheet, FilterPlot.xls, to experiment with different combinations of these five variables and view the response. It is located in the project file associated with this Application Note.

3 PSoC Switched Capacitor Universal Two Pole Filter
This section explains the detailed interworking and theory of switched capacitor filters, and how they are implemented in PSoC 1.

A topology for a state variable (bi-quad) switched capacitor filter is shown in Figure 1.

Figure 1. PSoC Bi-quad Filter

This bi-quad filter can be built with two switched capacitor blocks. They are both clocked with the same sample frequency, $f_s$. Equations 2 and 3 define the discrete time circuit operation of this filter.

$$
V_{out1} = V_{out1}z^{-1} - V_{in}\frac{C_1}{C_A} - V_{out2}\frac{C_2}{C_A} - (V_{out2} - V_{out2}z^{-1})\frac{C_4}{C_A} - (V_{in} - V_{in}z^{-1})\frac{C_4}{C_A} \tag{2}
$$

Equation 2
\[ V_{out2} = V_{out2}z^{-1} + V_{out2}z^{-4} \frac{C_3}{C_B} - (V_{in} - V_{in}z^{-1}) \frac{C_{pp}}{C_B} \]  

Equation 3

Equations 2 and 3 are used to solve the transfer functions in Equations 4 and 5.

\[ V_{out2} = -z^2 C_B C_p + 2z C_B C_p - z^2 C_B C_1 - C_B C_p + z C_B C_1 + z^2 C_{pp} C_2 + z^2 C_{pp} C_4 - 2z C_{pp} C_4 - z C_{pp} C_2 + C_{pp} C_A \\
V_{in} = z^2 C_B C_A - 2z C_B C_A + z C_2 C_3 + z C_4 C_3 - C_4 C_1 + C_B + C_A \]

Equation 4

\[ V_{out2} = \frac{z^2 C_{pp} C_A - 2z C_{pp} C_A + C_{pp} C_A + z C_p C_3 - C_p C_3 + z C_1 C_3}{z^2 C_B C_A - 2z C_B C_A + z C_2 C_3 + z C_4 C_3 - C_4 C_3 + C_B + C_A} \]

Equation 5

Applying the bilinear transform given in Equation 6 to transform Equations 4 and 5 results in the Laplace transfer Equations 7 and 8.

\[ z = -\frac{1 + \frac{s}{2f_s}}{1 - \frac{s}{2f_s}} \]

Equation 6

\[ H(s)_{output1} = -\frac{C_{pp} s}{C_3} \left( 1 + \frac{s}{f_s} \left( \frac{C_4}{C_2} + 1 \right) \right) + \frac{C_p C_B}{C_2 C_3} \left( \frac{s}{f_s} \right)^2 + \frac{C_p}{C_2 C_3} \left( \frac{1 + \frac{s}{2 f_s}}{f_s} \right) \]

Equation 7

\[ H(s)_{output2} = -\frac{C_{pp} C_4 \left( \frac{s}{f_s} \right)^2}{C_2 C_3} + \frac{C_p s}{C_2 f_s} \left( 1 - \frac{s}{f_s} \right) + \frac{C_p}{C_2 f_s} \left( 1 - \frac{1}{4} \left( \frac{s}{f_s} \right)^2 \right) \]

Equation 8

Note that the denominators for both Equations 7 and 8 are identical. This means the roll off frequency and damping values are identical for both outputs. Using Equation 1 as a template, the roll off frequency is shown in Equation 9.

\[ f_0 = \frac{f_s}{2\pi} \frac{\sqrt{C_2 C_3}}{\sqrt{C_A C_B - \frac{1}{2} C_4 - \frac{1}{4} C_3 C_3}} \]

Equation 9

Note that the roll off frequency is directly proportional to the sample frequency. This is a feature of switched capacitor filters. A minor change in the sample frequency changes the roll off frequency. Equation 10 defines the over sample ratio as being the ratio of these two frequencies.

\[ \text{Oversample} = \frac{f_r}{f_0} = 2\pi \frac{\sqrt{C_A C_B - \frac{1}{2} C_4 - \frac{1}{4} C_3 C_3}}{\sqrt{C_3 C_3}} \]

Equation 10

For example, a 5 kHz filter that is sampled at 250 kHz is said to have an over sample ratio of 50. Changing the roll off to 3.7 kHz only requires that the sample frequency be changed to 50 * 3.7 kHz or 185 kHz. Again, using Equation 1 as a template and using the solution for \( f_0 \) in Equation 9, the damping value is shown in Equation 11.
\[ d = \frac{C_4}{\sqrt{C_AC_B - \frac{1}{2}C_4 - \frac{1}{4}C_2C_3}} \sqrt{\frac{C_3}{C_2}} \]  
Equation 11

The high pass coefficient for the first output, from Equation 7, is extracted and shown in Equation 12.

\[ h_{hpl} = -\frac{C_pC_B}{C_AC_B - \frac{1}{2}C_4C_4 - \frac{1}{4}C_2C_3} \]  
Equation 12

Again, from Equation 7, the band pass coefficient is extracted. For reasons that will later become clear, this coefficient divided by the damping value is shown in Equation 13.

\[ \frac{h_{hpl}}{d} = -\frac{C_1C_B}{C_2C_3} \left( 1 + \frac{1}{2f_s} \right) \approx -\frac{C_1C_B}{C_4C_3} \]  
Equation 13

From Equation 8, the high pass, band pass, and low pass coefficients for the second output are extracted and shown in Equations 14, 15, and 16.

\[ h_{hpl} = -\frac{C_pC_A}{C_AC_A - \frac{1}{2}C_4C_4 - \frac{1}{4}C_2C_3} \]  
Equation 14

\[ h_{lp2} = -\frac{C_p}{C_2} \left( 1 - \frac{s}{f_s} \right) \approx -\frac{C_p}{C_4} \]  
Equation 15

\[ h_{lp2} = -\frac{C_1}{C_2} + \left( 1 - \frac{1}{4f_s} \right) \approx -\frac{C_1}{C_2} \]  
Equation 16

Note that each coefficient is directly proportional to \( C_1, C_p \) or \( C_{pp} \). Also note that none of these values are used to determine the roll off frequency and damping value.

4 Simple Rules for Filter Design

There are three steps to design a PSoC switched capacitor filter. They are:

1. Determine the roll off frequency, damping value and pass coefficients for the desired filter.
2. Using Equations 9 and 11, determine the values required for \( C_2, C_3, C_4, CA \) and \( C_B \) for the desired roll off frequency \( f_0 \) and damping value \( d \).
3. Using Equations 12 through 16, set the appropriate values to \( C_1, C_p \) and \( C_{pp} \) to meet the desired pass coefficients.
5 FilterCalc

FilterCalc.exe is a program to calculate all combinations of capacitor values that result in an acceptable roll off frequency and damping value. It is located in the project file associated with this Application Note. When the program is run, it will prompt you for the following information:

- Output file name
- Damping value
- Damping tolerance
- The desired roll off frequency
- Roll off tolerance
- Column clock (4x \(f_s\))

The program then calculates all combinations of the capacitors that meet these requirements. The acceptable combinations, if any, are written to the output file. The program also outputs to the terminal indicating the number of acceptable solutions.

For example, Figure 2 shows the terminal count given the following input:

- Output file is “test.csv”
- \(d = 1.414 \pm 5\%
- \(f_0 = 5\ kHz \pm 5\%
- \(f_s = 250\ kHz \ (f_{\text{ColumnClock}} = 1\ MHz)

The program finds 18 solutions that meet the input constraints. Because the output file has a “.csv” extension it can be viewed with a spread sheet. It is shown in Figure 3. Any of these 18 solutions are acceptable. The user can decide which best meets their specific requirements.
The rest of this Application Note will deal in the specifics for each type of filter.

6 Low Pass Filter

A low pass filter allows the passing of signals from DC up to some cutoff frequency, $f_{cutoff}$. The transfer equation for a two-pole low pass filter is given in Equation 17.

$$H(s)_{lp} = \frac{h_{lp}}{s^2 + \left(\frac{s}{2\pi f_0}\right) + 1} \quad \text{Equation 17}$$

A plot of a typical low pass filter is shown in Figure 4.

This plot and Table 1 show that the response is relatively flat for frequencies less than $f_0$. For frequencies greater than $f_0$, the signal falls off as the square of the frequency. At $f_0$ the output is attenuated by the damping value.
Table 2. Selected Points on Low Pass Transfer Function

<table>
<thead>
<tr>
<th>Gain</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(s)_{lp} = \frac{h}{s/2\pi f_0}$</td>
<td>$s/2\pi f_0 = 0$</td>
</tr>
<tr>
<td>$H(s)_{lp} = \frac{h}{s/2\pi f_0} = 1/10$</td>
<td>$s/2\pi f_0 = 1$</td>
</tr>
<tr>
<td>$H(s)_{lp} = \frac{h}{10 s/2\pi f_0}$</td>
<td>$s/2\pi f_0 = 10$</td>
</tr>
<tr>
<td>$H(s)_{lp} = \frac{h}{100 s/2\pi f_0}$</td>
<td>$s/2\pi f_0 = 100$</td>
</tr>
</tbody>
</table>

Note that the cut off frequency, $f_{cutoff}$, is defined as the frequency where the output is attenuated by 3 dB. It is not necessarily equal to $f_0$. Fortunately, many filter reference books have tables with the necessary roll off and damping values calculated for different types and orders of filters \[1\].

The transfer function shown in Equation 17 can be made by taking the $V_{out2}$ transfer Equation 8 and setting $C_p$ and $C_{pp}$ to zero. The low pass coefficient is shown in Equation 18.

$$h_{lp} = \frac{C_1}{C_2}$$  \hspace{1cm} \text{Equation 18}

The topology for a PSoC switched capacitor low pass filter is shown in Figure 5.

This is the topology used to implement the LPF2 User Module.

7 Low Pass Filter Example

The goal of this example is to construct the following filter:

- Two pole Bessel low pass filter
- Cut off frequency of 5 kHz
- An over sample ratio of 50 ($f_s = 250$ kHz)
- Unity gain

Standard tables from filter reference books\[1\] show that the filter is constructed with:

- $f_0 = 1.274 \times 5$ kHz = 6,370 kHz
- $d = 1.732$

The following figure shows the FilterCalc monitor.
There are 13 solutions that meet the design constraints. Figure 7 is the spreadsheet that lists them.

Any of these solutions meet the requirements. If a solution with the smallest roll off error is important, then the row 6 solution would be best. If the smallest damping error is important, the row 7 solution is best. If the largest value of $C_2$ is important, then choose the row 9 solution. (To reduce DC offset error caused by charge injection from the switches, it is desirable to keep the value of $C_2$ as high possible). For this example, the solution in row 9 is selected.

A value for $C_1$ can be calculated using Equation 18. For unity gain, $C_1$ must equal to $C_2$. The user module parameters are shown in Figure 8.
The user module placement is shown in Figure 9.

Figure 10 is a spectral plot for the filter.
Examination of the plot shows that the signal is down 3 dB around 5 kHz.

8 Low Pass Filters, the Easy Method

The earlier method was a lot of work to calculate a single set of filter values. Cypress has provided a more automated solution. From PSoC Designer, go to Help >> Documentation >> Filter Design. Figure 11 shows the spreadsheets available.
Opening up **LPF2 Design.xls** brings up a low pass filter design spreadsheet. See **Figure 12**. The filter characteristics are entered in the yellow cells. For this specific case, the filter is selected to have:

- A cutoff frequency of 5 kHz
- A Unity Gain (0 dB)
- A Bessel Response
- 250kHz Sample Freq

The derived filter requirements for damping value roll off frequency, and gain are shown in rows 16, 18, and 19.

A plot of the filter response including the effects of sampling and Nyquist frequency is provided. The **design procedure** is included in the box at the top right of the spreadsheet. This tool does not guarantee the best-fit solution; however, it does quickly provide a solution that meets all design requirements.

All of this is done without the user needing to know the damping and roll off values for their desired filter response. This same spreadsheet is available from PSoC Designer as a “Wizard” by selecting the Filter User Module then right clicking to get access to the Filter Design Wizard. The wizard has the advantage of automatically transferring the calculated values into that filter’s parameter locations. Also included with PSoC Designer is a spreadsheet for designing four-pole low pass filters (**LPF4 Design.xls**).
9 Band Pass Filter

A band pass filter allows the passing of signals around a defined median frequency. The transfer equation for a two-pole band pass filter is given in Equation 19.

\[ H(s) = \frac{H_{bp} \left( \frac{s}{2\pi f_0} \right)}{\left( \frac{s}{2\pi f_0} \right)^2 + d \left( \frac{s}{2\pi f_0} \right) + 1} \]

Equation 19

A plot of a typical band pass filter is shown in Figure 13.

Figure 13. FilterPlot-Generated Band Pass Filter

This plot and Table 3 show that the response peaks at \( f_0 \). It is equal to the pass coefficient divided by the damping value. For frequencies greater than \( 10f_0 \), the signal falls off proportionally to the frequency. For frequencies less than \( f_0/10 \), the signal falls off inversely to the frequency.

<table>
<thead>
<tr>
<th>Table 3. Selected Points on Band Pass Transfer Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>( H(s)<em>{bp} \approx h</em>{lp}/100 )</td>
</tr>
<tr>
<td>( H(s)<em>{hp} = h</em>{lp}/10 )</td>
</tr>
<tr>
<td>( H(s)<em>{lp} = h</em>{lp}/d )</td>
</tr>
<tr>
<td>( H(s)<em>{hp} = h</em>{hp}/10 )</td>
</tr>
<tr>
<td>( H(s)<em>{hp} = h</em>{hp}/100 )</td>
</tr>
</tbody>
</table>

The bandwidth of the band pass filter is defined as the difference between the upper (\( f_{upper} \)) and lower (\( f_{lower} \)) cutoff frequencies where the amplitude falls 3 dB below the peak value on its way out of the pass band. The center frequency (\( f_{center} \)) is the geometric mean of these two limits. They are shown in Equations 20 and 21.

\[ BW_{bp} = f_{upper} - f_{lower} \]

Equation 20

\[ f_{center} = \sqrt{f_{upper}f_{lower}} \]

Equation 21

An important parameter of band pass filters is the filter selectivity (\( Q \)). It is defined as the center frequency divided by the bandwidth and is shown in Equation 22.

\[ Q = \frac{f_{center}}{BW_{bp}} = \frac{\sqrt{f_{upper}f_{lower}}}{f_{upper} - f_{lower}} \]

Equation 22
To calculate the upper and lower cutoff points, Equation 19 is converted to the frequency format shown in Equation 23.

\[ H(f)_{bp} = \frac{h_{bp}}{\left( \frac{f - f_0}{f_0} \right) \sqrt{1 + d}} \]  

Equation 23

The amplitude of the transfer function will be down 3 db from the peak value when the imaginary part of the denominator in Equation 23 equals the real part of the denominator. This results in Equations 24 and 25.

\[ \frac{f_{upper}}{f_0} - \frac{f_0}{f_{upper}} = d \]  

Equation 24

\[ \frac{f_0}{f_{lower}} - \frac{f_{lower}}{f_0} = d \]  

Equation 25

Solving these equations results in Equations 26 and 27.

\[ f_{upper} = f_0 \sqrt{d^2 + 4 + d} \]  

Equation 26

\[ f_{lower} = f_0 \sqrt{d^2 + 4 - d} \]  

Equation 27

Substituting the values in Equation 26 and 27 into the center frequency and bandwidth of Equations 20 and 21, results in Equations 28 and 29.

\[ f_{center} = f_0 \sqrt{\frac{d^2 + 4 - d}{2} \sqrt{d^2 + 4 + d}} = f_0 \]  

Equation 28

\[ BW_{bp} = f_0 \sqrt{\frac{d^2 + 4 + d}{2}} - f_0 \sqrt{\frac{d^2 + 4 - d}{2}} = f_0 d \]  

Equation 29

These equations are used to calculate Q. It is shown in Equation 30.

\[ Q = \frac{f_{center}}{BW_{bp}} = \frac{f_0}{f_0 d} = \frac{1}{d} \]  

Equation 30

Multiple band pass filters can be cascaded to form higher order filters. As with low pass filters, many filter reference books have tables with the necessary center frequency and Q values calculated for different types and orders of band pass filters[1].

The band pass transfer function shown in Equation 19 can be implemented two ways. One method is to take the \( V_{out1} \) transfer Equation 7 and set \( C_0 \) and \( C_{bp} \) to zero. The band pass coefficient is shown in Equation 31.

\[ \frac{h_{bp1}}{d} = -\frac{C_1C_B}{C_4C_3} \]  

Equation 31

The topology for a PSoC switched capacitor band pass filter is shown in Figure 14.
This is the topology used to implement the BPF2 User Module.

An alternative method is to take the $V_{out2}$ transfer Equation 8 and set $C_1$ and $C_{pp}$ to zero. The alternative band pass coefficient is shown in Equation 32.

$$\frac{h_{bp2}}{d} = -\frac{C_p}{C_4}$$

Equation 32

The alternative topology is shown in Figure 15.

While there is no user module implementation of this alternate topology, a method for modification of an LPF2 User Module to perform this band pass function will be shown later.
10 BPF2 Filter Example

The goal of this example is to build a 1 kHz, 4 Vpp sinusoid generator. It is constructed by passing a 1 kHz square wave through a 1 kHz band pass filter to remove the unwanted extra harmonics. A block diagram is shown in Figure 16.

Figure 16. 1 kHz Sinusoid Generator Block Diagram

Note that the input to the filter is $V_{ref}$. It is converted to a +/-$V_{ref}$ square wave by connecting the PWM output to the filter block’s analog modulator input. The modulator toggles the input between $+V_{ref}$ and $-V_{ref}$ (RefHi and RefLo), these values are controlled by the RefMux parameter in the Global Resources of PSoC Designer. The block placement is shown in Figure 17.

Figure 17. Band Pass Example Block Placement

The requirements for the PWM8 are:
- 200 kHz input clock
- Period of 200
- Pulse width of 100
- Output connected to a modulator input (GOE[0])

Figure 18 shows the parameters required to implement a PWM with these requirements:
Figure 18. Parameters for PWM8_1

Equation 33 gives the Fourier series for a 1 kHz square wave with a +/- V\text{ref} amplitude.

\[ V_{\text{ref}} \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{\sin \left(2\pi f_0 (2n + 1) \right)}{2n + 1} \]

Equation 33

The frequency components are at f_0, 3f_0, 5f and so on. The hardest harmonic to remove is 3f_0. A band pass filter with a Q of four attenuates the third harmonic by 20 dB. (The third harmonic is already 10 dB lower than the primary frequency for a total attenuation of 30 dB.)

One requirement for this filter is to have a Pk-Pk value of 4 V. +V\text{ref}(\text{RefHi}) is 3.9 V and –V\text{ref}(\text{RefLo}) is 1.3 V, this is only 2.6 V Pk-Pk, so some gain is needed. Equation 34 calculates the peak gain required for an output of +/- 2 volts and a reference voltage of 1.3 volts.

\[ \text{PeakGain} = \frac{h_{\text{BP}}}{d} \frac{C_1}{C_4} = \frac{4V_{pp}}{2V_{\text{ref}}^2} = \frac{1.208}{\pi} \]

Equation 34

The requirements for the band pass filter are summarized below:

- Two pole Bessel band pass filter
- Center Frequency of 1 kHz
- Q of approximately 4 (d = ¼)
- An over sample ratio of 50 (f_s = 50 kHz)
- Peak Gain of 1.208

Figure 19 shows the FilterCal monitor.
There are 34 solutions that meet the requirements for Q and center frequency. They are shown in the spreadsheet in Figure 20.
Figure 20. Band Pass Example Solutions

Figure 21 shows the value of Q for each solution in column K. The value for the peak gain, when C1 = 1, has also been calculated in column L.
This data is then sorted by peak gain value. It is shown in Figure 22.
Three solutions have a peak gain value close to 1.208. The solution in row 26 is selected. The BPF2_1 parameters are shown in Figure 23.

Figure 22. Data Sorted by Peak Gain Value

![Data Sorted by Peak Gain Value](image)

Three solutions have a peak gain value close to 1.208. The solution in row 26 is selected. The BPF2_1 parameters are shown in Figure 23.

Figure 23. Band Pass Filter Parameters

![Band Pass Filter Parameters](image)
The modulator connection is made by selecting **Modulator Clock** to be **GlobalOutEven_0**, the output of the PWM.

Figure 24 shows that the output is in fact 4Vpp and has a frequency of 1 kHz.

![Figure 24. 4Vpp 1 kHz Output](image)

Note that the output is made up of 50 discrete samples per cycle. This is what is to be expected with a 50-kHz sampling clock (200-kHz column clock).

11 **May I have a Wizard Please**

There is design spreadsheet for two-pole and four-pole band pass filters. **BPF2 Design.xls** is opened and shown in Figure 25.

The filter characteristics are entered in the yellow cells. For this specific case, the filter is selected to have:

- A center frequency of 1 kHz
- Gain of 1.208 (1.64 dB)
- Bandwidth of 250 Hz
- Sample Frequency of 50kHz
The derived filter requirements for Q, roll off frequency, and gain are shown in rows 12, 14, and 15.

The user manipulates the $C_2$ (the cell in orange) while keeping track of the calculated Q in row 27. When satisfied with these two values, the calculated values for $C_A$, $C_B$, $C_3$, $C_4$ and $C_1$ can be found in rows 19, 20, 22, 24, and 26.

A plot of the filter response including the effects of sampling and Nyquist frequency is provided. For this example, the best fit came out with a gain of one. This is 16% below the desired value of 1.208. Some leeway is allowed in the Q value. Figure 26 shows the solution when the bandwidth requirement is lowered to 200 Hz.
With the same $C_2$, $C_4$ calculates to 13 and the gain is now 1.231 (a 2% error).

This same spreadsheet is available from PSoC Designer as a "Wizard" by selecting the Filter User Module then right clicking to get access to the Filter Design Wizard. The wizard has the advantage of automatically transferring the calculated values into the filter's parameter locations. Also included with PSoC Designer is a spreadsheet for designing four pole band pass filters (*BPF4 Design.xls*).

### 12 Alternate Band Pass Filter Example

The goal of this example is to construct the following filter:

- Two pole band pass filter
- Center frequency of 5 kHz
- $Q$ of 10 ($d = .1$)
- An over sample ratio of 50 ($f_s = 250$ kHz)
- Unity Peak Gain.

Figure 27 shows the FilterCalc monitor given these constraints.
Four Solutions meet the design constraints. They are shown in Figure 28.

The solution in row 7 has the smallest center frequency error. It is the one selected.

The topology of the alternate band pass filter shown in Figure 13 is very close to the low pass filter topology shown in Figure 6. A low pass filter can be converted to an alternate band pass filter by:

- Setting \( C_1 \) to zero
- Setting \( C_p \) value in software

The user module placement is shown in Figure 29.
The user module parameters are shown in Figure 30.

Figure 30. FauxBP Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>FauxBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Module</td>
<td>LFF2</td>
</tr>
<tr>
<td>Version</td>
<td>3.00</td>
</tr>
<tr>
<td>C1</td>
<td>0</td>
</tr>
<tr>
<td>C2</td>
<td>16</td>
</tr>
<tr>
<td>C3</td>
<td>1</td>
</tr>
<tr>
<td>C4</td>
<td>13</td>
</tr>
<tr>
<td>CA</td>
<td>32</td>
</tr>
<tr>
<td>CB</td>
<td>32</td>
</tr>
<tr>
<td>Input</td>
<td>ACB00</td>
</tr>
<tr>
<td>AnalogBus</td>
<td>AnalogOutBus_1</td>
</tr>
<tr>
<td>CompBus</td>
<td>DISABLE</td>
</tr>
<tr>
<td>Polarity</td>
<td>Inverting</td>
</tr>
<tr>
<td>Modulated</td>
<td>Clock Alert</td>
</tr>
</tbody>
</table>

Note that C1 is set to zero. The correct value and input connection must be set for Cp. C1 is the ACap of the filter’s input block, while Cp is the CCap of the same block.

Cp must be connected to the buffer located in ACB00. Figure 31 shows that setting the input for ACap (C1) to ACB00 also set the CCap (Cp) input to ACB00.
Figure 31 confirms the A and C inputs are correctly configured to connect to ACB00.

Example Code 1 shows the program that starts the filter and also configures the Ccap (Cp) value.

Equation 32 shows that for unity peak gain, \( C_p \) must equal \( C_4 \). Software is used to set the lower 5 bits of the register \( ASC10CR \) to 13. This is shown in example Code 2.

Code 1

```c
void main(void) {
    PGA_1_Start(PGA_1_HIGHPower);
    FauxBP_Start(FauxBP_HIGHPower);

    // set CCap (Cp) to 13
    ASC10CR2 |= 0x01;

    while(1);
}
```

Figure 32 shows a spectral plot of this filter.
Figure 32. Q=10 Alternate Band Pass Filter Spectral Plot

Examination of the plot shows that the signal has a center frequency of 5 kHz. It also is 40 dB down a decade away from the center frequency. This is consistent for a 5 kHz band pass filter with a Q of 10.

13 High Pass Filter

A high pass filter allows the passing of signals greater than some cutoff frequency $f_{cutoff}$. The transfer equation for a two-pole high pass filter is given in Equation 35.

$$
H(s)_{hp} = \frac{h_0 \left( \frac{s}{2\pi f_0} \right)^2}{\left( \frac{s}{2\pi f_0} \right)^2 + d \left( \frac{s}{2\pi f_0} \right) + 1}
$$

Equation 35

A plot of a typical high pass filter is shown in Figure 33.
Figure 33. FilterPlot-Generated High Pass Filter

Table 4. Selected Points on High Pass Transfer Function

<table>
<thead>
<tr>
<th>Gain</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(s)hp = 0</td>
<td>s/2πf0 = 0</td>
</tr>
<tr>
<td>H(s)hp = hlp/1002</td>
<td>s/2πf0 = 1/100</td>
</tr>
<tr>
<td>H(s)hp = hlp/102</td>
<td>s/2πf0 = 1/10</td>
</tr>
<tr>
<td>H(s)hp = hlp/d</td>
<td>s/2πf0 = 1</td>
</tr>
<tr>
<td>H(s)hp = hhp</td>
<td>s/2πf0 = 10</td>
</tr>
<tr>
<td>H(s)hp = hlp</td>
<td>s/2πf0 = 100</td>
</tr>
</tbody>
</table>

Note that the cut off frequency, fcutoff, is defined as the frequency where the output is attenuated by 3 dB. It is not necessarily equal to f0.

Fortunately, many filter reference books have tables with the necessary roll off and damping values calculated for different types and orders of filters [1].

The high pass transfer function shown in Equation 35 can be implemented two ways.

One method is to take the Vout1 transfer Equation 7 and set C11 and Cpp to zero. The high pass coefficient is shown in Equation 36.

\[
h_{hp1} = -\frac{C_p C_B}{C_A C_B - \frac{1}{2} C_3 C_4 - \frac{1}{4} C_2 C_3} \tag{Equation 36}
\]

The topology for a PSoC switched capacitor high pass filter is shown in Figure 34.
An alternative method is to take the $V_{\text{out}2}$ transfer Equation 8 and set $C_1$ and $C_P$ to zero. The alternative high pass coefficient is shown in Equation 37.

$$h_{hp/2} = -\frac{C_{hp}C_A}{C_A C_B - \frac{1}{2} C_3 C_4 - \frac{1}{4} C_2 C_3}$$

Equation 37

The alternative topology is shown in Figure 35.

There are no user module implementations in either topology.

13.1 Why Not?

Switched capacitor filters sample the input at some sample frequency, $f_s$. At the Nyquist limit ($f_s/2$), the signal frequency will start to alias back toward DC. Switched capacitor filters cannot distinguish a DC input from an input at the sampling frequency.

This is not a problem for low pass filters. The Nyquist point, being half the over sample ratio, is far down the attenuation curve. For a 100 over sample two-pole low pass filter, the output signal is down 68 dB at the Nyquist point. It is 56 dB down for a filter with an over sample ratio of 25.

It is just the opposite for a high pass filter. At the Nyquist point, pretty much all the signal is passed through. Signals past the Nyquist frequency are aliased and are generally useless. This limits the bandwidth of a high pass filter to be from the cutoff frequency up to the Nyquist frequency effectively a band pass filter.
This is not unique to PSoC switched capacitor filters. Implementing a well performing high pass filter requires very high over sample ratio (at least several thousand). Hyper large over sample ratios require a large ratio of capacitor sizes. This uses a significant amount silicon area, thus, rendering them economically impractical.

13.2 Notch Filter

A notch filter allows the passing of signals except around a defined median frequency. It is a combination of equal amounts of the low pass and high pass coefficients. The transfer equation for a two-pole notch filter is given in Equation 38.

\[
H(s)_{\text{notch}} = \frac{h_{lp} \left( \frac{s}{2 \pi f_0} \right)^2 + h_{hp}}{(s/2 \pi f_0)^2 + d \left( \frac{s}{2 \pi f_0} \right) + 1} : h_{lp} = h_{hp} \\
\]

Equation 38

A plot of a typical notch filter is shown in Figure 36.

Figure 36. Filter Plot-Generated Notch Filter

This plot and Table 5 show that the response is zero at \( f_0 \). At some distance away from \( f_0 \), the signal is passed relatively unattenuated.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H(s)_{\text{notch}} \approx h )</td>
<td>( s/2 \pi f_0 = 1/100 )</td>
</tr>
<tr>
<td>( H(s)_{\text{notch}} \approx h )</td>
<td>( s/2 \pi f_0 = 1/10 )</td>
</tr>
<tr>
<td>( H(s)_{\text{notch}} = 0 )</td>
<td>( s/2 \pi f_0 = 1 )</td>
</tr>
<tr>
<td>( H(s)_{\text{notch}} \approx h )</td>
<td>( s/2 \pi f_0 = 10 )</td>
</tr>
<tr>
<td>( H(s)_{\text{notch}} \approx h )</td>
<td>( s/2 \pi f_0 = 100 )</td>
</tr>
</tbody>
</table>

Table 5. Selected Points on Notch Transfer Function

The bandwidth of the notch is defined as the difference between the upper (upper) and lower (lower) cutoff frequencies where the amplitude falls 3 dB. The center frequency (\( f_{\text{center}} \)) is the geometric mean of these two limits. They are shown in Equations 39 and 40.

\[
BW_{\text{notch}} = f_{\text{upper}} - f_{\text{lower}} \\
f_{\text{center}} = \sqrt{f_{\text{upper}} f_{\text{lower}}} \\
\]

Equation 39

Equation 40
To calculate the upper and lower cutoff points, the amplitude of Equation 38 is shown in Equation 41.

$$H(f)_{\text{notch}} = \frac{h \left( f_0 - f \right)^2}{h \left( \frac{f}{f_0} - 1 \right)^2 + d^2}$$

Equation 41

Equation 42 shows the point where the signal is 3 dB down.

$$H(f)_{\text{notch}} = \frac{h}{\sqrt{2}}$$

Equation 42

Equations 40 and 41 are combined to find the two solutions. They are shown in Equation 43 and Equation 44.

$$f_{\text{upper}} = f_0 \frac{\sqrt{d^2 + 4 + d}}{2}$$

Equation 43

$$f_{\text{lower}} = f_0 \frac{\sqrt{d^2 + 4 - d}}{2}$$

Equation 44

Substituting the values in Equation 43 and 44 into the center frequency and bandwidth in Equations 39 and 40, results in Equations 45 and 46.

$$f_{\text{center}} = f_0 \frac{\sqrt{d^2 + 4 - d} \sqrt{d^2 + 4 + d}}{2} = f_0$$

Equation 45

$$BW_{lp} = f_0 \frac{\sqrt{d^2 + 4 + d}}{2} - f_0 \frac{\sqrt{d^2 + 4 - d}}{2} = f_0 d$$

Equation 46

The notch bandwidth is proportional to the damping value. The center frequency is the roll off frequency. The transfer function shown in Equation 38 can made two different ways.

The first is by taking the \( V_{out2} \) transfer Equation 8 and setting \( C_p \) to zero. This is shown in Equation 47.

$$H(s)_{\text{notch}} = \frac{C_p C_A \left( C_4 C_5 \right)^2 + \left( C_i \right)^2}{C_p C_A \left( C_4 C_5 \right)^2 + \left( C_i \right)^2} + \frac{C_4 s}{C_5 f_s} + 1$$

Equation 47

The topology for such a filter is shown in Figure 37. The low pass and high pass coefficients are shown in Equation 48.

$$h_{lp2} = \frac{C_p C_A - \frac{1}{4} C_i C_3}{C_p C_A - \frac{1}{2} C_i C_4 - \frac{1}{4} C_i C_3} = h_{hp2} = -\frac{C_i}{C_2}$$

Equation 48
This filter has the advantage of only using two switched capacitor blocks. The disadvantage is that interaction between the two blocks near the roll off frequency keeps it from functioning well for values of Q much greater than one. The second way the notch filter transfer Equation 38 can also be expressed is as the original input minus a band pass filter output. This is shown in Equation 49.

\[ H(s)_{\text{notch}} = h - \frac{h_{bp} \left( \frac{s}{2\pi f_0} \right)^2}{\left( \frac{s}{2\pi f_0} \right)^2 + d \left( \frac{s}{2\pi f_0} \right)} + 1 \]

Equation 49

A block diagram of such a filter is shown in Figure 38.

Figure 38. Notch Filter Block Diagram

This filter is implemented using a band pass filter plus an additional switched capacitor block functioning as a DiffAmp. It requires an additional block to implement but is more able to implement high Q notch filters.
14 Notch Filter Example

For this example, the alternate band pass example will be modified to include a notch output. The block placement is shown in Figure 39.

Figure 39. Band Pass/Notch Block Placement

A DiffAmp has been added to subtract the buffer input from the band pass filter output. The parameters for the DiffAmp block are shown in Figure 40.
The filter connection is made to the **BCap** input. It is the negative input. The band pass filter inverts the gain so the input into the **ACap** input must be inverted. Setting **ASign** negative does this. The only software change is to start the extra PGA User Module.

**Figure 40. DiffAmp Parameters**

**Figure 41** is a spectral plot of this filter.

**Figure 41. Q=10 Alternate Band Pass Filter Spectral Plot**

Examination of the plot shows that the signal has a notch at 5 kHz. The 3 dB points are approximately 500 Hz apart. This is consistent for a 5 kHz notch filter with a Q of 10.
15 Elliptical Filter

Similar to the notch filter, an elliptical filter allows the passing of signals only when they are passed around a defined median frequency. The difference is that they are no longer equal amounts of the low pass and high pass coefficients. The transfer equation for a two-pole notch filter is given in Equation 50.

$$H(s)_{\text{elliptical}} = \frac{h_{lp} \left( \frac{s}{2\pi f_0} \right)^2 + s}{s^2 + d \left( \frac{s}{2\pi f_0} \right)^2 + 1} : h_{lp} \neq h_{hp}$$

Equation 50

A plot of a typical elliptical low pass filter is shown in Figure 42.

Figure 42. FilterPlot-Generated Elliptical Low Pass Filter

This plot and Table 6 show that the response is zero at points determined by \(f_0, h_{hp}, \) and \(h_{lp}\). At some distance away from \(f_0\), the signal is determined by its relative pass coefficient.

Table 6. Selected Points on Elliptical Transfer Function

<table>
<thead>
<tr>
<th>Gain</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H(s)<em>{\text{elliptical}} = h</em>{lp})</td>
<td>(s/2\pi f_0 = 1/100)</td>
</tr>
<tr>
<td>(H(s)<em>{\text{elliptical}} = h</em>{hp})</td>
<td>(s/2\pi f_0 = 1/10)</td>
</tr>
<tr>
<td>(H(s)_{\text{elliptical}} = 0)</td>
<td>(s/2\pi f_0 = (h_{lp}/h_{hp})^{1/2})</td>
</tr>
<tr>
<td>(H(s)<em>{\text{elliptical}} = h</em>{hp})</td>
<td>(s/2\pi f_0 = 10)</td>
</tr>
<tr>
<td>(H(s)<em>{\text{elliptical}} = h</em>{lp})</td>
<td>(s/2\pi f_0 = 100)</td>
</tr>
</tbody>
</table>

Note that an elliptical filter can either be high pass or low pass. At some defined point, the output rapidly drops to zero.

The transfer function shown in Equation 38 can be made two different ways. The first is by taking the \(V_{\text{out2}}\) transfer Equation 8 and setting \(C_p\) to zero. This is shown in Equation 51.

$$H(s)_{\text{elliptical}} = \frac{C_p C_A}{C_p C_A - \frac{1}{4} C_4 \left( \frac{s}{f_s} \right)^2} + \frac{C_4}{C_2} s + 1$$

Equation 51
The low pass and high pass coefficients are shown in Equation 52.

$$h_{p2} = \frac{C_{mp} C_A - \frac{1}{4} C_4 C_3}{C_A C_3 - \frac{1}{2} C_5 C_4 - \frac{1}{4} C_2 C_4} = h_{p2} = -\frac{C_1}{C_2}$$  \hspace{1cm} \text{Equation 52}

The topology for a PSoC switched capacitor elliptical filter is shown in Figure 43.

**Figure 43. PSoC Two Pole Elliptical Filter**

You may notice this topology looks similar to notch filter. The only difference is that the pass coefficients are no longer equal. This filter has the advantage of only using two switched capacitor blocks. The disadvantage is that interaction between the two blocks near the roll off frequency keeps it from functioning well for values of Q much greater than one. Fortunately, when implementing low pass and high pass elliptical filters, the desired Q is most certainly never much larger than one.

16 **Elliptical Filter Example**

For this example, the Bessel low pass example will be modified to add a high pass coefficient one-tenth the low pass value.

The requirements are:
- Two pole Bessel low pass filter
- Cut off frequency of 5 kHz
- An over sample ratio of 50 ($f_s = 250$ kHz)
- Unity low pass gain
- -20 dB high pass gain

Standard tables from filter reference books [1] show that the filter is constructed with:
- $f_0 = 1.274 \times 5$ kHz = 6,380 kHz
- $d = 1.732$

The coefficients calculated for the low pass part were:
- $C_1 = 3$
- $C_2 = 3$
- $C_3 = 8$
- $C_4 = 31$
- $C_A = 32$
- $C_B = 32$

Substituting the known values into Equation 52 results in Equation 53 with a single unknown variable.
Equation 53

\[ h_{pp} = 0.1 = \frac{C_{pp}^{32} - \frac{3 \cdot 8}{4}}{32 \cdot 32 - \frac{8 \cdot 31 - 3 \cdot 8}{4}} \]

Solving Equation 53 results in Equation 54.

\[ C_{pp} = 2.98 \approx 3 \]

Equation 54

Substituting this value into Equation 53 results in the actual coefficient show in Equation 55.

\[ h_{pp} = 0.1 = \frac{3 \cdot 32 - \frac{1}{4} \cdot 3 \cdot 8}{32 \cdot 32 - \frac{8 \cdot 31 - 1 \cdot 3 \cdot 8}{4}} = 1.007 \approx 1 \]

Equation 55

The block placement is shown in Figure 44.

The topology of the elliptical filter is very close to a low pass filter. All that is required to convert the LPF2 User Module to an elliptical filter is to set the value and input connection for \( C_{pp} \). This is done in software.

\( C_{pp} \) is the BCap of the filter’s output block. It must be connected to the buffer located in ACB0.

The default setting for the input for BCap (\( C_{pp} \)) is ACB00. No software is required to connect it.

Example Code 4 shows the program that starts the filter and also configures the BCap (\( C_{pp} \)) value.
Note that the output goes to zero at about 21 kHz. This is consistent for a filter with $f_0 = 6.38$ kHz and a low pass-to-high pass ratio of $10 (6380*10^{\frac{1}{2}})$. Frequencies past this notch are a little over 20 dB below the low frequency inputs. Again, this is consistent with the design constraints.

17 Summary

Universal two pole filters are the building blocks of all filters. It can be thought of as having five variables:

- Roll frequency, $f_0$
- Damping Value, $d$
- Low pass coefficient, $h_{lp}$
- Band Pass Coefficient, $h_{bp}$
- High Pass Coefficient, $h_{hp}$

PSoC has the ability to control and implement all five of these variables. These filter blocks can be cascaded together to implement more complex filters. Filter reference books will have tables of damping values and roll off frequencies required to implement more complex filters.

FilterCalc is a program that will assist the user in determining the best possible capacitor values for their specific filter requirements.

Filter design spreadsheets are available with the PSoC Designer documentation. Automated design wizards are available for placed filter modules.

Filter design for a PSoC system is very straightforward given a good filter reference book and the tools shown in this Application Note.
18 References

- Active Filter Cook Book, Don Lancaster, Synergetics Press, 2002

About the Author

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Title: Principal Applications Engineer
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