

*UNIVERSITY of PENNSYLVANIA*  
DEPARTMENT of ELECTRICAL and SYSTEMS ENGINEERING

**Electrical Circuits and Systems II Laboratory**  
**ESE206**

**Filter Lab**

**Design of a 3<sup>rd</sup> order Butterworth Filter using the  
Universal Filter Chip UAF42**

***Goals:***

- Design a Butterworth filter
- Using the pole-zero plot to design the filter.
- Getting familiar with the Universal Filter Chip UAF42 and learning to read the datasheet
- Measuring the frequency and time response of a filter.

***Introduction:***

A Butterworth filter has the maximally flat response in the pass-band. At the cut-off frequency,  $\omega_c$ , the attenuation is -3dB. Above the -3dB point the attenuation is relatively steep with a roll off of -20dB/decade/pole. The figure below shows the frequency response of such a filter.

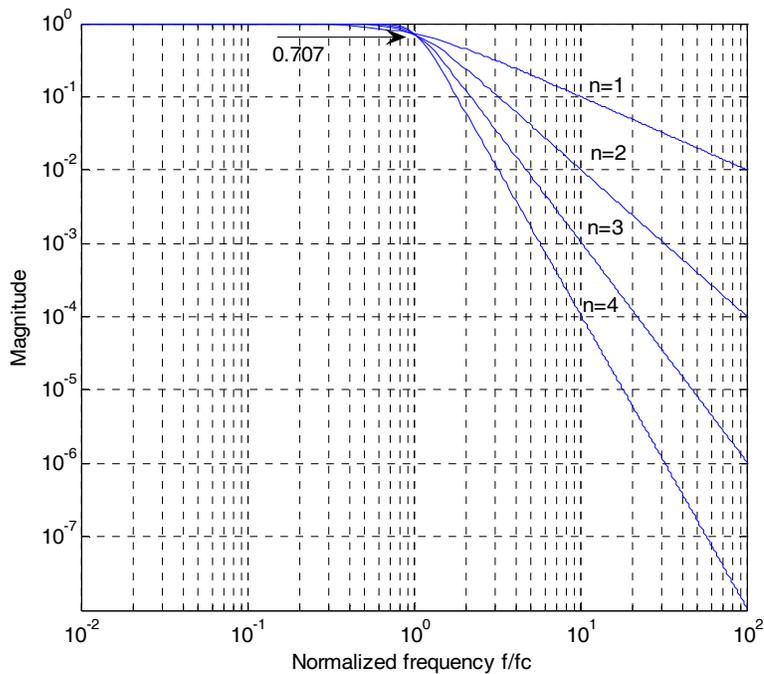


Figure 1: Frequency response of a Butterworth filter of order n.

The poles of a Butterworth filter are located on a circle with radius  $\omega_c$  and are spaced apart by an angle  $180^\circ/n$  in which n is the order of the filter (number of poles). The first pole is located  $180^\circ/2n$  from the  $j\omega$  axis, as shown in the figure below.

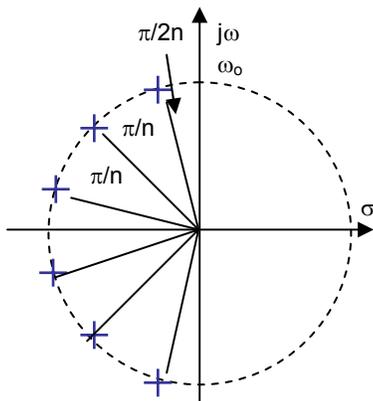


Figure 2: Poles of a Butterworth filter.

The filter can be implemented in a variety of ways. We will be using the “Universal Active Filter” chip, UAF42 of Burr-Brown. This chip contains several op-amps which on chip capacitors and resistors. By adding a few external resistors one can implement a low-pass, high-pass and band-pass filter. The on-chip capacitors have a value of 1000pF. A schematic of the circuit is shown in the figure below.

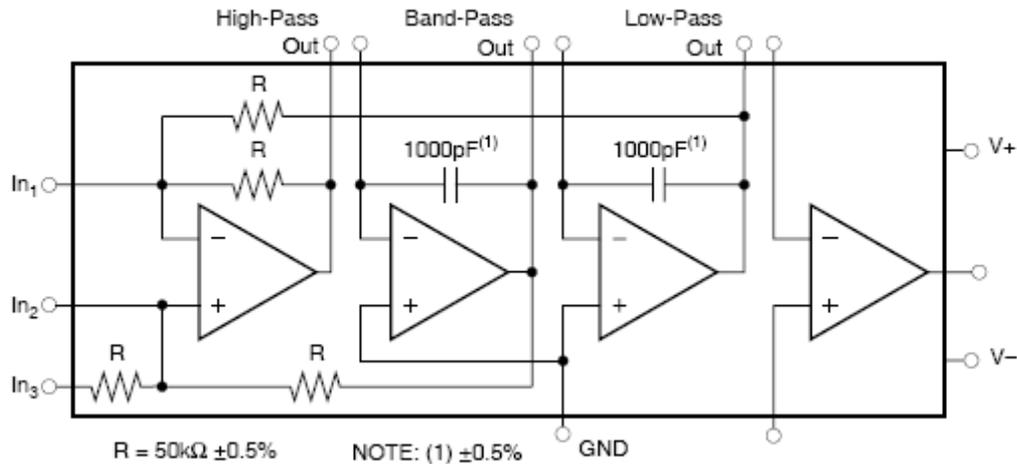


Figure 3: Universal Active Filter chip UAF42 (Ref: Burr-Brown UAF PDS-1070H, 1998).

Notice that there is an auxiliary opamp available for additional use (e.g. as amplifier, buffer or for implementation of an additional pole). The first three opamps implement a second order system (either as low-pass, band-pass or high-pass). The transfer function for a low-pass filter can be written as,

$$\frac{V_{oLP}}{V_{in}} = \frac{A_{LP}\omega_o^2}{s^2 + 2\zeta\omega_o s + \omega_o^2} = \frac{A_{LP}\omega_o^2}{s^2 + \frac{\omega_o s}{Q} + \omega_o^2}$$

The high-pass and band-pass have the same denominator but with different nominator (with a double and single zero, respectively). This circuit implements two poles. To realize higher order filters one need to add additional circuits. For a 4<sup>th</sup> order filter one can cascade two 2<sup>nd</sup> order filters. For this lab assignment you will realize a 3<sup>rd</sup> order filter which will require a 2<sup>nd</sup> order circuit (two poles) and a 1<sup>st</sup> order circuit (one pole). The first order low-pass circuit can be easily implemented using the auxiliary amplifier. A possible circuit is given below.

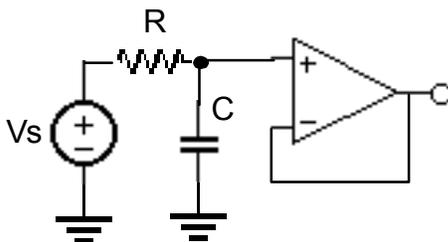


Figure 4: 1<sup>st</sup> order low-pass filter.

## **Pre-lab assignment:**

1. Read the Data sheet of the Universal Active Filter, UAF42  
<http://focus.ti.com/lit/ds/symlink/uaf42.pdf>

2. Design a 3<sup>rd</sup> order Butterworth non-inverting filter with the following specs: cut-off frequency  $f_o = \omega_o / 2\pi$  of 1kHz and unity gain in the pass-band:

- Plot the poles on the complex s-plane for the 3<sup>rd</sup> order filter (similar to Figure 2 above).
- Find the value of the damping factor  $\zeta$  and quality factor Q for the 2<sup>nd</sup> order circuit (that implement the complex conjugate poles).
- Give the value of the 3<sup>rd</sup> pole.

3. Using the configuration of Figure 1 (page 5) in the datasheet UAF42, find the values of the external resistors  $R_{F1}$ ,  $R_{F2}$ , and  $R_Q$  to realize the required  $\omega_o$  and quality factor Q. Note, there is no need to use the DOS filter design program. Simplify the equations for  $\omega_o = \omega_n$ , Q and  $A_{LP}$ , knowing that  $R_1 = R_2$  and  $C1 = C2$ . In addition, if one makes  $R_G = 50k\Omega = R_1$ , one can use input no. 2 (pin no. 2) and there is no need to add an external  $R_G$ . In addition, by not including  $R_G$ , one effectively makes  $R_Q$  infinitely large. This will further simplify the expressions for  $\omega_o = \omega_n$ , Q and  $A_{LP}$ . One now needs to find only the two external resistors  $R_{F1}$  and  $R_{F2}$ .

4. Find the value of the capacitor of the circuit that implements the real pole. Use for R a value of 10k $\Omega$ .

5. It is a good idea to simulate the transfer function (Bode plot) of the designed filter using MATLAB to make sure the design is correct. In addition, you can simulate the response to a unit step function;

- Write down the transfer function of the filter
- Using Matlab plot the Bode diagram of the filter and make sure it give the required response.

## **Lab Experiment**

### **Equipment:**

1. UAF42 chip (Burr-Brown)
2. HP function generator/waveform generator (HP 33120A)
3. Power supply
4. HP digital oscilloscope HP 54600
5. Resistors
6. Capacitor

## In-Lab Experiment:

1. Using the Universal Filter Chip UAF42 build the 3<sup>rd</sup> order Butterworth filter, a non-inverting circuit. Use the component values you calculated in the pre-lab. For the resistors use values that are as close to the calculated ones as possible. For the power supply use +/- 15V (check the data sheet for ratings). The pinout of the UAF42 is given in the figure below. For the in description, consult the datasheet (UAF42).

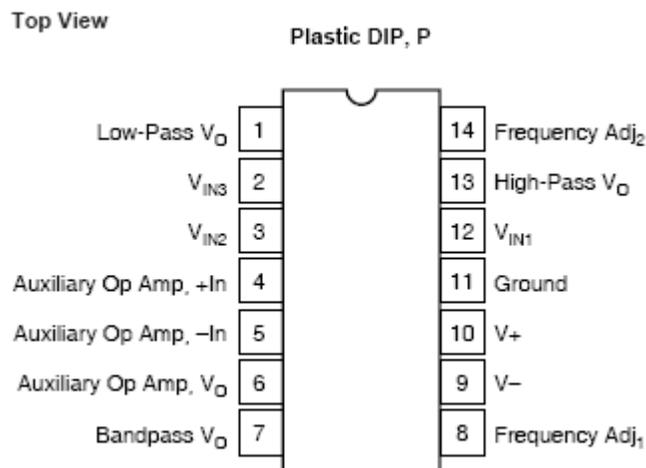


Figure 5: Pin out of the UAF42

2. **Frequency Domain Characterization:** Measure the frequency response of the low-pass filter, high-pass and band-pass filters (notice that the chip implements the three filters). Apply a sinusoidal input signal of 1V amplitude and vary the frequency on a log scale (e.g. 10Hz, 20Hz, 40Hz, 80Hz, 100Hz, 200 Hz,...). Measure the amplitude and phase. When you notice that the amplitude and phase changes quickly you can increase the frequency in finer steps. Plot the transfer function (magnitude in dB and phase) versus frequency (log scale). Confirm that the -3dB point is 1kHz. What is the roll-off (in dB/dec)?
3. **Time Domain Characterization:** Apply a square wave to the input and measure output of the low-pass, high-pass and band-pass filters. For the low-pass filter what is the amount of overshoot (ringing), rise time, fall time? Take a screen shot of the oscilloscope traces for each of the outputs. Can you explain the output? For the low-pass filter, compare the result with the one obtained from Matlab.

## ***To hand-in***

Write your lab report, according to the [guidelines](#), summarizing the experiments and results obtained in the lab. Summarize the results in table format. Compare the measurements with the simulated results (MATLAB) and discuss any differences, if any. Do this for both the frequency domain and time domain measurements. It will be instructive to plot the Matlab results on the same graph as the measured values.

## **References:**

1. Horowitz and Hill, The Art of Electronics, Cambridge University Press, 2<sup>nd</sup> Editions, 1989 (Chapter 5).
2. Sedra, Smith, Microelectronics, Oxford University Press, 5<sup>th</sup> edition, 2004 (Chapter 12).
3. J. Nilsson, S. Riedel, Electric Circuits, 7<sup>th</sup> edition, Prentice Hall, 2005.
4. UAF42 [Universal Active Filter datasheet](#).
5. Application Bulletin, [Filter Design Program for the UAF42 Universal Active Filter](#), Burr-Brown, 1993.

Jan Van der Spiegel  
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