UNIVERSAL ACTIVE FILTER

FEATURES

- LOW COST
- SMALL SIZE
  Single wide DIP package
- FULLY CHARACTERIZED PARAMETERS
- HYBRID CONSTRUCTION
- IMPROVED PERFORMANCE
  1% frequency accuracy
  Q range of 0.5 to 500
  NPO capacitors and thin-film resistors
  Uncommitted op amp included

BENEFITS

- SAVES PRINTED CIRCUIT BOARD SPACE
- SAVES DESIGN TIME
  Design directly from this data sheet
  Versatile building block for filter design
- HIGH RELIABILITY
- HIGH STABILITY
**DESCRIPTION**

UAF41 is a versatile two-pole active filter. It uses a three operational amplifier double integrator feedback loop to generate a complex pole pair (two conjugate poles). The location of the poles in the complex plane (and thus the natural frequency and Q) are determined by external, user supplied resistors. Either three or four resistors are used depending on the particular configuration chosen.

The UAF41 produces three transfer functions simultaneously - low-pass, high-pass, and bandpass - which are available at three separate outputs. The fourth basic transfer function - the band-reject or notch - can be obtained simply by summing the high-pass and low-pass outputs using the uncommitted amplifier (A4) contained in the UAF41. The uncommitted op amp can also be used to add a single-pole response for complex filters requiring an odd number of poles.

More complex higher-order filters can readily be obtained by cascading UAF's. This is easily done with the UAF41 since the high input impedance and low output impedance associated with the operational amplifiers used prevents the series connected stages from interacting (e.g., no frequency pull due to following stage loading). This data sheet contains the design procedures for an easy selection of resistor values for the stagger tuning of cascaded stages.

The versatility of the UAF41 makes it a general purpose building block for a wide variety of active filter applications. Its universal nature, ease of use, small size, and low cost allows the user the convenience of keeping units on hand for immediate use whenever a filter requirement arises.

**TRANSFER FUNCTION**

The UAF41 uses the state variable technique to produce a basic second order transfer function. The equations describing the three outputs available are:

\[
T_{\text{Low-Pass}} = \frac{A_{12} \omega_m^2}{s^2 + (\omega_m/Q) s + \omega_m^2}
\]

\[
T_{\text{Bandpass}} = \frac{A_{12} (\omega_m/Q)s}{s^2 + (\omega_m/Q) s + \omega_m^2}
\]

\[
T_{\text{High-Pass}} = \frac{A_{12} s^2}{s^2 + (\omega_m/Q) s + \omega_m^2}
\]

To obtain band-reject characteristics the low-pass and high-pass outputs are summed to form a pair of j\omega axis zeros:

\[
T_{\text{Band-Reject}} = \frac{A (s^2 + \omega_m^2)}{s^2 + (\omega_m/Q) s + \omega_m^2}
\]

where \(A_{12} = A_{12p} = A\).

The state variable approach uses two op amp integrators (A2 and A3 in the simplified schematic below) and a summing amplifier (A1) to provide simultaneous low-pass, bandpass, and high-pass responses. One UAF41 is required for each two poles of low-pass or high-pass filters and for each pole-pair of bandpass or band-reject filters.

**FIGURE 1. UAF41 Schematic.**

*Analog Circuit Functions*

*Burr-Brown IC Data Book* 5-83 Vol. 33
## SPECIFICATIONS

### ELECTRICAL

Typical at 25°C and with rated supply unless otherwise noted.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>UA841</th>
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<tr>
<td><strong>INPUT</strong></td>
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<tr>
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<td>Input Voltage Range</td>
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<tr>
<td>Input Resistance</td>
<td>50kΩ</td>
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<td><strong>TRANSFER CHARACTERISTICS</strong></td>
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<tr>
<td>Frequency Range (f0)</td>
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<tr>
<td>f0 Accuracy</td>
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<tr>
<td>f0 Stability</td>
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<tr>
<td>Q Range</td>
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</tr>
<tr>
<td>Q Stability</td>
<td>±0.01%/°C</td>
</tr>
<tr>
<td>@ f0 Q ≥ 10</td>
<td>±0.03%/°C</td>
</tr>
<tr>
<td>@ f0 Q ≥ 104</td>
<td>±1%</td>
</tr>
<tr>
<td>Q Repeatability at f0 Q ≥ 104</td>
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<tr>
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<tr>
<td>(at L.P. output with unity gain)</td>
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<tr>
<td>Output Current</td>
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<td><strong>UNCOMMITTED AMP CHARACTERISTICS</strong></td>
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<tr>
<td>Storage Temperature Range</td>
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</table>

**NOTES:**
1. For noninverting input configuration with Aep. 1.
2. The tolerance of external frequency determining resistors must be added to this figure.
3. T.C.R. of external frequency determining resistors must be added to this figure.
4. See Performance Curves for Vout vs F curve.
5. Q stability varies with the value of Q and the resonant frequency f0.
6. See Performance Curves for full power response curve.
7. Re = Req < 100Ω at low-pass output with unity gain.
8. Measured at the bandpass output with Q @ 50 over DC to 50kHz.
9. The current required to drive Re and Req (external) as well as C1 and C2 must come from the current.
10. For supplies below ±10V, Qmax will decrease slightly; filters will operate below 15V.

### MECHANICAL

14-Pin Plastic DIP Package

<table>
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<th>MIN</th>
<th>MAX</th>
<th>MIN</th>
<th>MAX</th>
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<td>0.36</td>
<td>10.79</td>
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<tr>
<td>B</td>
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<td>0.25</td>
<td>5.69</td>
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<tr>
<td>C</td>
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<td>0.12</td>
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<td>0.20</td>
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<td>K</td>
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<td>L</td>
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<td>0.20</td>
<td>0.61</td>
<td>0.61</td>
</tr>
</tbody>
</table>

ROW SPACING: 7.83mm (0.300")
WEIGHT: 1.1 grams max

Pin material and plating composition conform to method 2003 (solderability) of MIL-STD-883 (except paragraph 3.2)

### PIN CONNECTIONS

- Pin 1 - LOW-PASS OUTPUT
- Pin 2 - FILTER INPUT 3
- Pin 3 - FILTER INPUT 2
- Pin 4 - AUXILIARY AMP + INPUT
- Pin 5 - AUXILIARY AMP - INPUT
- Pin 6 - AUXILIARY AMP OUTPUT
- Pin 7 - BANDPASS OUTPUT
- Pin 8 - FREQUENCY ADJUST
- Pin 9 - NEGATIVE SUPPLY
- Pin 10 - POSITIVE SUPPLY
- Pin 11 - COMMON
- Pin 12 - FILTER INPUT 1
- Pin 13 - HIGH-PASS OUTPUT
- Pin 14 - FREQUENCY ADJUST

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**DESIGN PROCEDURE SUMMARY**

This summary gives the design steps for the proper application of UAF41s and for the selection of the external components. More detailed information on filter theory pertinent to some of the steps can be found in the reference sources listed on last page.

**DESIGN STEPS:**

1. Choose the type of function (low-pass, bandpass, etc.), type of response (Butterworth, Bessel, etc.), number of poles, and cutoff frequency based on the particular application.
   
   If the transfer function is band-reject see Band-Reject Transfer Function before proceeding to step 2.

2. Determine the normalized low-pass filter parameters (f1 and Q) based on the type of response and number of poles selected in step 1. See Normalized Low-Pass Parameters.

3. If the actual response desired is low-pass go to step 4.
   For other responses a transformation of variables must be made (low-pass to bandpass or low-pass to high-pass). See Low-Pass Transformation.

4. Determine the actual (denormalized) cutoff frequency, f0, by multiplying f1 by the actual desired cutoff frequency. See Denormalization of Parameters.

5. Pick the desired UAF configuration (noninverting, inverting or bi-quad) see Configuration Selection Guide and UAF41 Configuration and Design Equations.

6. Decide whether to use design equations “A” or “B”.
   See Design Equations “A” and “B”.

7. Calculate Rf1 and Rf2, See Natural Frequency and UAF Configurations and Design Equations.


9. Select the desired gain for each UAF and calculate the corresponding R0 and R0. See Gain (A) and UAF41 Configurations and Design Equations.

**NORMALIZED LOW-PASS PARAMETERS**

Usual active filter design procedure involves using normalized low-pass parameters. Table 1 is provided to assist in this step for the more common filter responses. Table II is a BASIC program which allows f1 and Q to be calculated for any desired ripple and number of poles for the Chebyshev response. Consult the reference on last page for other information.

Note that for bandpass and high-pass filters, complex conjugate pole pairs in the actual filter correspond to single poles in the normalized low-pass model. Thus four poles in Table I would correspond to four-pole pairs (eight poles) in a bandpass or high-pass filter.
Filters with an odd number of poles show one \( f_s \) with no corresponding \( Q \) value. This represents a simple RC network that is required for odd pole filters. This RC network with a cutoff frequency equal to \( f_s \) times the overall filter cutoff frequency should be placed in series with the first UAF two-pole section. The uncommitted internal op amp with an external RC network can be used for this purpose.

The cutoff frequency determined by the Table 1 filter parameters is (1) the -3dB frequency of the Butterworth response and of the Bessel response and (2) the frequency at which the amplitude response of the Chebyshev filters passes through the maximum ripple band (to enter the stop band). A filter that is designed as a low-pass filter will not give the corresponding response as a band-pass filter.

**Table I. Low-Pass Filter Parameters.**

<table>
<thead>
<tr>
<th>NUMBER OF POLES</th>
<th>BUTTERWORTH</th>
<th>BESSEL</th>
<th>CHEBYSHEV</th>
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</thead>
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<tr>
<td></td>
<td>( f_n(1) )</td>
<td>( Q )</td>
<td>( f_n(1) )</td>
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<tr>
<td>2</td>
<td>1.0</td>
<td>0.70711</td>
<td>1.2742</td>
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<td>2.5629</td>
<td>2.19237</td>
<td>1.2257</td>
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(1) -3dB Frequency

(2) Frequency at which amplitude response passes through the ripple band.

**NORMALIZED LOW-PASS CHEBYSHEV**

Table II gives a BASIC program for the determination of \( f_s \) and \( Q \) for a general normalized Chebyshev low-pass filter of any ripple and number of poles. Program inputs are the number of poles (\( N \)) and the peak-to-peak ripple (\( R \)). Program outputs are \( f_s \) and \( Q \), which are used exactly as the values taken from Table I.

**BAND-REJECT TRANSFER FUNCTION**

The band-reject is achieved by summing the high-pass and low-pass UAF outputs. Either of the configurations in Figures 3 and 4 can be used to provide the band-reject function if they are used as shown in Figure 2.

The 15k\( \Omega \) resistor is adjusted for maximum rejection. The circuit in Figure 2 is applicable when using design equations \( A_{in} = A_{out} \). When design equations \( B \) are used (\( A_{in} = 10A_{out} \)), the resistor at pin 1 must be 10 times the resistor at pin 13 to obtain equal pass-band gains above and below \( f_s \).

In either case, the four external UAF resistors (\( R_{OL}, R_{01}, R_{13}, \) and \( R_{22} \)) should be calculated for \( f_s \) and \( Q \) of the

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for a reject filter desired and for \( A_{bp} \) to equal the desired band gain. An input constraint is that the input voltage times \( A_{bp} \) must not exceed the rated peak-to-peak voltage of the bandpass output, or clipping will result. Note that the band-reject function is suitable only for a single UAF section. In a multisection filter the inputs to successive stages are "preconditioned" by the preceding stages.

### Table II. Low-Pass Chebyshev Program.

110 PEN THIS IS A NORMALIZED LOW-PASS CHEBYSHEV PROGRAM
120 PEN BY BURR BROWN INC.
130 PRINT "NORMALIZED CHEBYSHEV"
140 PRINT "LOW-PASS FILTER"
150 PRINT "BY BURR BROWN"
160 PRINT "NUMBER OF POLES"
170 PRINT "PEAK-TO-PEAK RIPPLE IN DB?"
180 INPUT N
190 INPUT M
200 PRINT "SUPPLY LEVEL"
210 PRINT "FOR K"
220 PRINT "= M*1000"
230 PRINT "TO PIN 14"
240 PRINT "ADJUST FOR BEST SENSITIVITY"
250 PRINT "3 = EXP(2*1.414213562)
260 PRINT "S = EXP(2*1.772453851)
270 PRINT "C = 1/S"
280 PRINT "R = 1/C"
290 PRINT "K = 1/R"
300 PRINT "Q = S/R"
310 PRINT "P = 1/Q"
320 PRINT "f_high (KHz) = 1/2 * pi * f_0 * Q"
330 PRINT "f_low (KHz) = 1/2 * pi * f_0 / Q"
340 PRINT "f_0 = 1/2 * pi * f_high * Q"
350 PRINT "f_0 = 1/2 * pi * f_low * Q"
360 PRINT "K = P/Q"
370 PRINT "f_high = f_0 * Q"
380 PRINT "f_low = f_0 / Q"
390 PRINT "f_0 = 1/2 * pi * f_high * Q"
400 PRINT "f_0 = 1/2 * pi * f_low * Q"
410 PRINT "f_high = f_0 / Q"
420 PRINT "f_low = f_0 * Q"
430 NEXT K
440 END

### Offset Error Adjustment

DC offset errors will be minimized by grounding pin 3 through a resistor equal to \( 1/2 \) the value of \( R_1 \) or \( R_2 \). The DC offset adjustment shown here may be used if required.

Offset errors will increase with increases in \( R_p \).

### Low-Pass Transformation

#### Low-Pass to High-Pass

The following simple transformation may be used for high-pass filters:

\[
\frac{1}{f_{hi}} = \frac{1}{f_{lo}} \times \frac{1}{Q_{hi}}
\]

Where:

- \( f_{hi} \) is the high-pass frequency
- \( f_{lo} \) is the low-pass frequency
- \( Q_{hi} \) is the high-pass quality factor

#### Low-Pass to Bandpass

The low-pass to bandpass transformation to generate \( f_0 \) (bandpass) and \( Q \) (bandpass) is much more complicated. It is tedious to do by hand but can be accomplished with the BASIC program given in Table III. This program automates the transformation

\[
s = \frac{p}{2} \pm \sqrt{(p/2)^2 - 1}
\]

### Table III. Low-Pass to Bandpass BASIC Transformation Program. (See last page of this PDS.)
PROGRAM INPUTS:
1. \( f_c \) - From Table I for the low-pass filter of interest
2. \( Q \) - From Table I
3. \( Q_{BP} \) - Desired \( Q \) of the bandpass filter

For filters with an odd number of poles a \( Q \) of 0.5 should be used where \( Q \) is not given in Table I. Enter \( 10^6 \) for \( Q \) when transforming zeros on the imaginary axis.

The program transforms each low-pass pole into a bandpass pole pair. Thus a three-pole low-pass input, would result in the pole positions for a three-pole pair bandpass filter requiring three UAF stages.

DENORMALIZATION OF PARAMETERS
Table I shows filter parameters for many 2- to 8-pole normalized low-pass filters. The \( Q \) and the normalized undamped natural frequency, \( f_0 \), for each two-pole section are shown. The \( Q \) values do not have to be denormalized and may be used directly as described in the Design Procedure Summary. \( f_0 \) must be denormalized by multiplying it by the desired cutoff frequency of the actual overall filter to obtain the required frequency, \( f_c \) for the design formulas. As an example, consider a 4-pole low-pass Bessel filter with a cutoff frequency of 1000Hz. The first stage would be designed to an \( f_c \) of 1432.41Hz and a \( Q \) of 0.52193 while the second stage would have an \( f_c \) of 1605.94Hz and a \( Q \) of 0.80554. To combine the two stages into the composite filter the low-pass output of the first stage (pin 1) would be connected to the input resistors (\( R_c \)) of the second stage.

DESIGN EQUATIONS "A" AND "B"
1. For \( f_c \) below 8kHz, either of equations "A" or "B" may be used.
2. For \( f_c \) above 8kHz, equations "B" must be used. If equations "A" were used above 8kHz, the filter could become unstable.
3. Equations "A" are for the UAF as it is supplied. When using equations "B", a 5.49k\( \Omega \) resistor must be placed in parallel with \( R_1 \) (between pins 12 and 13).
4. The values of \( R_{BP} \) and \( R_{PI} \) calculated with equations "B" are approximately one-third of those calculated with equations "A". Thus there may be an advantage in using equation "B" at low frequencies. Using equation "B" would require use of one more resistor, but that would not alter or affect filter performance in any manner.
5. Using the negative gain values for \( A_{LP} \) or \( A_{BP} \) or \( A_{HP} \) could result in the negative values for resistors \( R_c \) and \( R_Q \). So the absolute value of the gain should always be used in the equations.

GAIN (A)
1. The gain (\( V/V \)) of each filter section is:
   \( A_{LP} \) - for low-pass output - gain at DC
   \( A_{BP} \) - for bandpass output - gain at \( f_c \)
   \( A_{HP} \) - for high-pass output - gain at high frequencies.
2. Refer to Performance Curves for full power response.

When selecting the gain, ensure that the limits of the curve are not exceeded for the desired voltage range.

NATURAL FREQUENCY (\( f_0 \))
1. \( f_c \) for each one pole-pair bandpass filter is the center frequency (\( f_c \)). \( f_c \) is defined as \( f_c = \sqrt{f_f f_l} \) where \( f_f \) is the lower -3dB point and \( f_l \) is the upper -3dB point of the pole pair response.
2. To obtain \( f_c \) below 100Hz using practical resistor values, capacitors may be paralleled with \( C1 \) and \( C2 \) to reduce the size of \( R_{BP} \) and \( R_{PI} \). If capacitors are added in parallel,
\[
R_{BP} (\text{new}) = R_{BP} (\text{old}) \left( \frac{1000 \mu F}{C + 1000 \mu F} \right)
\]
where \( R_{BP} (\text{new}) \) is the new lower value frequency resistor, \( C \) is the value of the two external capacitors placed across \( C1 \) and \( C2 \) (between pins 7 and 8 and pins 1 and 14 and \( R_{BP} (\text{old}) \) is the value calculated in the simplified design equations.

Q-FACTOR
1. For bandpass filters \( Q = \frac{f_c}{\text{3dB bandwidth}} \)
2. When designing low-pass filters of more than two poles, best results will be obtained if the two pole sections with lower \( Q \) are followed by the sections with higher \( Q \). This will eliminate any possibility of clipping due to high gain ripple in high \( Q \) sections.
3. \( Q \) repeatability (\( Q \) change from unit-to-unit) is typically \( \pm 5\% \) for \( LQ \) products less than \( 10^4 \). The \( Q \) repeatability error increases as the \( LQ \) product increases to approximately \( \pm 10\% \) for \( LQ \) products near \( 10^4 \).

Q-PROCEDURE
1. If the "f, times Q" product is greater than \( 10^4 \), it is possible for the measured filter \( Q \) to be different from the calculated value of \( Q \). This effect is the result of non-ideal characteristics of operational amplifiers. It can be compensated for by introducing the parameter \( Q_f \) into the design equations.
2. Calculate the \( LQ \) product for the filter. If the product is above \( 10^4 \), locate the corresponding \( LQ \) product in the Performance Curves. Divide \( f_c \) by \( Q_f \) to obtain \( Q \). Use \( Q_f \) as indicated in the design equations. For \( LQ \) products below \( 10^4 \), \( Q_f = Q \).
CONFIGURATION SELECTION GUIDE

It is possible to configure the UAF41 three different ways. Each configuration produces features that may or may not be desirable for a specific application. This selection guide is given to assist in determining the most advantageous configuration for a particular application.

<table>
<thead>
<tr>
<th></th>
<th>NONINVERTING INPUT</th>
<th>INVERTING INPUT</th>
<th>BI QUAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outputs Available</td>
<td>BP, LP and HP</td>
<td>BP, LP and HP</td>
<td>BP and LP</td>
</tr>
<tr>
<td>Outputs Inverted with respect to the Input</td>
<td>BP</td>
<td>HP and LP</td>
<td>BP and LP</td>
</tr>
<tr>
<td>Q &amp; Gain Independent of Frequency Resistors?</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Type of Q Variation With Changes in RF</td>
<td>Constant Q</td>
<td>Constant Q</td>
<td>Constant Bandwidth</td>
</tr>
<tr>
<td>Other Advantages</td>
<td>May eliminate one external resistor (use internal Rf as RG)</td>
<td></td>
<td>Rf and Rg are small at high frequencies. Easy single-supply operation.</td>
</tr>
</tbody>
</table>

Summary: The Bi-Quad filter is particularly useful as a bandwidth filter if the filter bandwidth must be kept constant as the center frequency is varied. If Q must be kept constant (i.e., constant Q of a bandpass or maintaining a constant response of a low-pass or high-pass) one of the other two configurations should be used. The Bi-Quad also has the advantage that Rf and Rg are smaller than with the other two configurations (this is especially useful at high frequencies). The noninverting input configuration has the advantage that for App = 1, Rg = 50kΩ; therefore Rf (internal) may be used so that only three external resistors are needed (Rf, Rg, Rg). For single supply operation of the UAF41 in bi-quad filters, bias pin 3 and pin 11 to 1/2 Vcc.

UAF41 CONFIGURATIONS AND DESIGN EQUATIONS

**NONINVERTING INPUT CONFIGURATION**

<table>
<thead>
<tr>
<th>Simplified Design Equation</th>
<th>&quot;A&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rf2 = Rf1</td>
<td>( \frac{1}{10^6} )</td>
</tr>
<tr>
<td>2. App = 0 to 0.1</td>
<td>0.103 x 10^7</td>
</tr>
<tr>
<td>3. Rf1 = 0 to 0.1</td>
<td>0.103 x 10^7</td>
</tr>
<tr>
<td>4. Rf1 = 0 to 0.1 App = 0.1</td>
<td>0.103 x 10^7</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Simplified Design Equation</th>
<th>&quot;B&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rf2 = Rf1</td>
<td>( \sqrt{3.14} \times 10^5 )</td>
</tr>
<tr>
<td>2. App = 0.1 to 0.01</td>
<td>3.14 x 10^5</td>
</tr>
<tr>
<td>3. Rf1 = 0.1 to 0.1 App = 0.1</td>
<td>3.14 x 10^5</td>
</tr>
<tr>
<td>4. Rf1 = 0 to 0.1 App = 0.1</td>
<td>3.14 x 10^5</td>
</tr>
</tbody>
</table>

**FIGURE 3. Noninverting Input Configuration.**
**INVERTING INPUT CONFIGURATION**

![Inverting Input Configuration Diagram]

**BI-QUAD CONFIGURATION**

![Bi-Quad Configuration Diagram]

**DETAILED TRANSFER FUNCTION EQUATIONS**

The following equations show the action of all the internal and external UAF41 filter components. They are not required for the regular design procedure but could be used if a detailed analysis is required.

**NONINVERTING INPUT CONFIGURATION**

1. \( \omega_0^2 = \frac{R_2}{R_1 R_2 R_3 C_1 C_2} \)
2. \( Q = \frac{R_2}{R_1} \)
3. \( Q_{A_2} = Q_{A_1} R_2 \)
4. \( A_{O_2} = R_2 Q_{O_2} \)
5. \( A_{O_1} = R_2 Q_{O_1} \)
6. \( A_P = \frac{R_2}{R_0} \)
7. \( A_{O_0} = \frac{1}{R_0 Q_{O_0}} \)
8. \( A_{P_0} = \frac{1}{R_0 Q_{P_0}} \)

**INVERTING INPUT CONFIGURATION**

1. \( \omega_0^2 = \frac{R_2}{R_1 R_2 R_3 C_1 C_2} \)
2. \( Q = Q_{A_1} R_2 \)
3. \( Q_{A_2} = Q_{A_1} R_2 \)
4. \( A_{O_2} = \frac{R_2}{R_0} \)
5. \( A_{O_1} = \frac{1}{R_0 Q_{O_1}} \)
6. \( A_P = \frac{1}{R_0 Q_{P_0}} \)

**BI-QUAD CONFIGURATION**

1. \( \omega_0^2 = \frac{R_2}{R_1 R_2 R_3 C_1 C_2} \)
2. \( Q = Q_{A_1} R_2 \)
3. \( A_{O_2} = \frac{R_2}{R_0} \)
4. \( A_{O_1} = \frac{1}{R_0 Q_{O_1}} \)
5. \( A_P = \frac{1}{R_0 Q_{P_0}} \)
6. \( A_{P_0} = \frac{1}{R_0 Q_{P_0}} \)

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ACTIVE FILTER DESIGN EXAMPLES USING THE DESIGN PROCEDURE OUTLINED IN DESIGN STEPS SECTION.

Example 1.

It is desired to design a three-pole, 0.5dB ripple, Chebyshev High-Pass Filter; the cutoff frequency \( f_c = 2 \text{kHz} \), Gain \( A_{HP} = +1 \).

Step 1.
The type of transfer function (high-pass), the type of response (Chebyshev), number of poles (3), and the cut-off frequency \( f_c \) are chosen depending upon the particular application and are stated in the example.

Step 2.
Normalized low-pass filter parameters \( f_l \) and \( Q \) are obtained from Table I (or from program shown in Table II).

Complex Poles:
- \( f_c = 1.068853 \)
- \( Q = 1.7062 \)

Simple Pole:
- \( f_c = 0.626456 \)

Step 3.
Now, since the actual response desired is high-pass, the low-pass to high-pass transformation must be made as previously discussed in Low-Pass Transformation.

\[
f_l(\text{high-pass}) = \frac{1}{f_l(\text{low-pass})} \quad Q_{HP} = Q_{LP}
\]

For Complex Poles:

\[
f_l = \frac{1}{0.626456} = 0.935582
\]

and \( Q = 1.7062 \)

For Simple Pole: \( f_l = \frac{1}{0.626456} = 1.596281 \)

Step 4.
Now, determine the actual (denormalized) frequency.

\( f_l = f_c \times f_l = 2 \times 1.068853 = 1871.2 \text{Hz} \)

Step 5.
Refer to the Configuration Selection Guide. Since the gain required is positive, the HP output is not inverted with respect to the input. Therefore, the noninverting input configuration must be selected. Note that the HP output is not available with the Bi-Quad configuration.

Step 6.
Since \( f_l < 8 \text{kHz} \), Equations "A" would be used.

Step 7.
For the Complex Poles Stage of the filter, using the equations "A".

\[
R_{P1} = R_{P2} = \frac{1.592 \times 10^4}{1871.2} = 85.08k\Omega
\]

Step 8.
\( L_1Q = 1871.2 \times 1.7062 \times 3.19 \times 10^3 \)
\( f_1Q < 10^5 \)
\( Q_{SP} = Q = 1.7062 \)

Step 9.
\[
A_{HP} = A_{LP} = 1.7062 \times 1 \times 1.7062
\]
\[
R_o = \frac{5.0 \times 10^4 \times 1.7062}{1.7062 \times 1.7062} = 29.3k\Omega
\]
\[
R_o = \frac{5.0 \times 10^4}{2 \times 1.7062 - 1.7062 - 1} = 70.8k\Omega
\]

The above-obtained resistor values are for the complex pole pair of the first stage of the required active filter. The simple pole obtained as outlined below, using the uncommitted op amp in the UAF41 makes the second stage of the required filter.

For the simple pole \( f_l \) was obtained in step 3.

\( f_l = 1.596281 \)

The actual (denormalized) frequency = \( f_c \times f_l \)

\( = 2 \text{kHz} \times 1.596281 = 3192.6Hz \)

Now, \( f = \frac{1}{2\pi RC} \)

\[
RC = \frac{1}{2\pi f} = \frac{1}{2\pi \times 3192.6} = 4.9851 \times 10^{-3}
\]

Choosing \( C = 2200\mu F \) (or any convenient value),

\[
R = \frac{4.9851 \times 10^{-3}}{2200 \times 10^{-12}} = 22.66k\Omega
\]

Note:

\( R \) and/or \( C \) may be chosen in any convenient manner to obtain the desired \( RC \) product.

The overall circuit for the required filter is shown below:

FIGURE 6. Overall Circuit - Example 1.
Example 2.
It is desired to design a 4-pole Butterworth, Bandpass Filter, with Q = 25, $f_c = 19\text{kHz}$ and $A_{sp} = 1$.
Using the computer program shown in Table III, the following values of $f_0$ and Q are obtained:

$$f_0 = 1.0142435, \ Q = 35.36541$$

and

$$f_0 = 0.9859565, \ Q = 35.35886$$

Using the above shown values of Q and $f_0$, we now will proceed to design the two stages of filter separately. Composite gain will be $\leq 1$. Any one of the three configurations shown in the Configuration Selection Guide can be used. We will select the noninverting input configuration.

For Stage 1:

$$f_s = 19\text{kHz} \times f_0 = 19\text{kHz} \times 1.0142435 = 19270.6\text{Hz}$$

Since $f_s > 8\text{kHz}$, equations "B" would be used.

$$R_{r1} = R_{r2} = \frac{5.033 \times 10^7}{19270.6} = 2.6118k\Omega$$

$$L_Q = \frac{19270.6 \times 35.36541}{6.815136 \times 10^3} = 36.25k\Omega$$

Since $L_Q > 10^4$, locate the corresponding $f_0Q_T$ from the Performance Curves.

Divide $L_Q$ by $f_0$ to obtain $Q_T$.

Thus $Q_T = 48.78$

$$R_Q = \frac{5.0 \times 10^3 \times 35.36541}{1 \times 48.78} = 36.25k\Omega$$

$$R_Q = \frac{5.0 \times 10^7}{3.48 \times 47.78 - 35.37} = 298.7\Omega$$

For Stage 2:

Following the same procedure as shown for Stage 1 above, the values shown below are obtained.

$$L_Q = 6.624 \times 10^4$$

Using the Performance Curves,

$$Q_T = 48.04$$

$$R_{r1} = R_{r2} = 2.6867k\Omega$$

$$R_Q = 36.8k\Omega$$

and $R_Q = 303.4\Omega$

The overall circuit for the required filter is shown below.

![Overall Circuit - Example 2](image)

Example 3.
It is desired to design a 5-pole Bessel, Low-Pass Filter with $f_s = 3.3\text{kHz}$ and $A_{sp} = 1$.
From Table I the following values of $f_0$ and Q are obtained.

Complex Poles:

$$f_0 = 1.55876$$

$$Q = 0.56354$$

$$f_0 = 1.75812$$

$$Q = 0.91652$$

Simple Pole:

$$f_0 = 1.59470$$

Using the above shown values of $f_0$ and Q, we now will proceed to design the three stages of filter separately. Any one of the three configurations can be used. We will select inverting configuration.

For Stage 1:

$$f_s = 3.3\text{kHz} \times f_0 = 3.3\text{kHz} \times 1.55876 = 5144\text{Hz}$$

Since $f_s < 8\text{kHz}$, equations "A" would be used.

$$R_{r1} = R_{r2} = \frac{1.592 \times 10^7}{5144} = 30.95k\Omega$$

$$L_Q = \frac{5144 \times 0.56354}{2.9 \times 10^3} = 50k\Omega$$

$$A_{sp} = Q_T = Q = 0.56354$$

$$R_Q = \frac{5 \times 10^7 \times 0.56354}{0.56354} = 50k\Omega$$

$$R_Q = \frac{5 \times 10^7}{2 \times 0.56354 + 0.56354 - 1} = 72.4k\Omega$$

For Stage 2:

$$f_s = 3.3\text{kHz} \times f_0 = 3.3\text{kHz} \times 1.75812 = 5802\text{Hz}$$

Since $f_s > 8\text{kHz}$, equations "A" would be used.

$$R_{r1} = R_{r2} = \frac{1.592 \times 10^7}{5802} = 27.44k\Omega$$

$$L_Q = \frac{5 \times 0.91652 \times 0.91652}{5.32 \times 10^3} = 20.24k\Omega$$

$$A_{sp} = Q_T = Q = 0.91652$$

$$R_Q = \frac{5 \times 10^7 \times 0.91652}{0.91652} = 50k\Omega$$

$$R_Q = \frac{5 \times 10^7}{2 \times 0.91652 - 0.91652 - 1} = 28.58k\Omega$$

For Stage 3:

$$f_s = 3.3\text{kHz} \times f_0 = 3.3\text{kHz} \times 1.50470 = 4966\text{Hz}$$

For the simple pole,

$$R_C = \frac{1}{2\pi f_{sp} \times 4966} = 3.2049 \times 10^{-3}$$

1300pF (or any convenient value)
USEFUL REFERENCES

TABLE III. Low-Pass to Bandpass BASIC Transformation Program.

```
20 INPUT "FN, Q, AND Q(BANDPASS)";F,Q,QBP
30 Y=F*cos(1-(1/(2*Q))^2)
40 X=-F/(2*Q)
50 PX=X;PY=Y
60 FOR I=1 TO 2
70 SX=PX/(2*QBP);SY=PY/(2*QBP)
80 PX=(SX^2-SY^2)-1;PY=2*SX*SY
90 T=-ATN(PY/PX)
95 T=T+3.14159264
100 IF T>0 THEN 120
110 T=2*3.14159264+T
120 T=T/2
130 A=SQRT(SQRT(PX^2+PY^2))*COS(T)
140 B=SQRT(SQRT(PX^2+PY^2))*SIN(T)
150 SX=AX+ASY=SY+B
160 F=SQRT(SX^2+SY^2)
170 Q=-F/(2*SQ)
180 PRINT "FX=":F;"Q=":Q
190 IF Y=O THEN 220
200 PX=X;PY=-Y
210 NEXT I
220 STOP
230 END
```