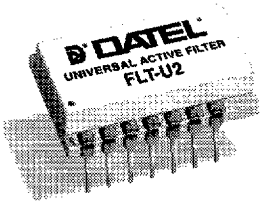
DATEL®
INNOVATION and EXCELLENCE

FLT-U2
Universal Active Filter

FEATURES

- State variable filter
- Output to 200kHz
- 2-Pole response
- LP, BP or HP functions
- Q range from 0.1 to 1,000
- Resonant frequency accuracy ±5%
- Frequency stability ±0.01%/°C
- Low-noise operational amplifiers
- –55 to +125°C operation
- Low cost



GENERAL DESCRIPTION

The FLT-U2 is a universal active filter that uses the state-variable active-filter principle to implement a second order transfer function. Three committed operational amplifiers are used for the second-order function, while a fourth uncommitted operational amplifier can be used as a gain stage, summing amplifier, buffer amplifier, or to add another independent real pole.

Two-pole lowpass, bandpass and highpass transfer functions are available simultaneously from three different outputs, and notch and allpass functions are available by combining these outputs in the uncommitted operational amplifier. To realize higher order filters, several FLT-U2s can be cascaded. Frequency tuning is done by two external resistors and Q tuning by a third external resistor. For resonant frequencies below 50Hz, two external tuning capacitors must be added. Precise tuning of the resonant frequency is done by varying one of the resistors around its calculated value.

The internal operational amplifiers in the FLT-U2 have 3MHz gain-bandwidth products and a wideband input noise specification of only 10nV/√Hz. This results in considerably improved operation over most other competitive active filters which employ lower-performance amplifiers. By proper selection of external components, any of the popular filter types such as Butterworth, Bessel, Chebyshev or Elliptic may be designed.

Two models are available for operation over the commercial, 0 to +70°C, and military, –55 to 125°C, temperature ranges.

INPUT/OUTPUT CONNECTIONS

PIN	FUNCTION	PIN	FUNCTION
1	R_Q	16	NO PIN
2	R_{IN}	15	NO PIN
3	HIGHPASS OUTPUT	14	STAGE 2 INPUT
4	+15V SUPPLY	13	BANDPASS OUTPUT
5	LOWPASS OUTPUT	12	–15V SUPPLY
6	+IN BUFFER	11	BUFFERED OUTPUT
7	STAGE 3 INPUT	10	–IN BUFFER
8	NO PIN	9	GROUND

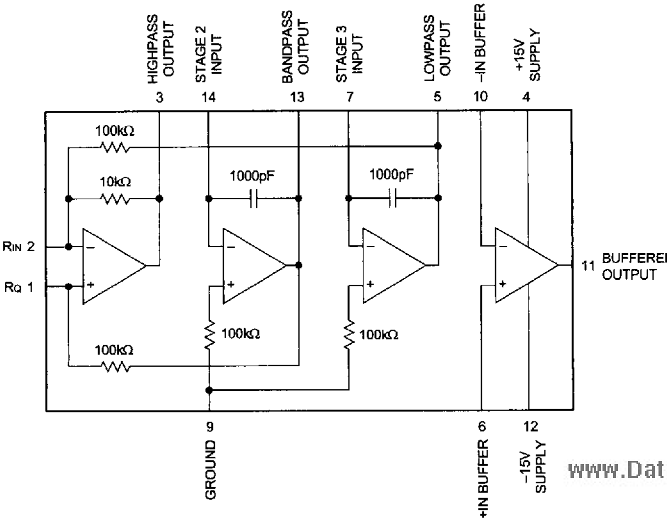


Figure 1. Functional Block Diagram

FUNCTIONAL SPECIFICATIONS

(Typical at +25°C and ±15V supplies unless otherwise noted.)

FILTER CHARACTERISTICS	MIN.	TYP.	MAX.	UNITS
Frequency Range ①		10^{-6} to 200		kHz
Q Range ①		0.1 to 1,000		
f_0 Accuracy		±5		%
f_0 Temperature Coefficient		±0.01		%/°C
Voltage Gain ①		0.1 to 1.0		V/V
AMPLIFIER CHARACTERISTICS				
Input Offset Voltage	—	±0.5	±6	mV
Input Bias Current	—	±40	±500	nA
Input Offset Current	—	±5	±200	nA
Input Impedance	—	5	—	MΩ
Input Com. Mode Voltage Range	±12	—	—	Volts
Input Voltage Noise, wideband	—	10		nV/√Hz
Output Voltage Range	±10	—	—	Volts
Output Current	±5	—	—	mA
Open Loop Voltage Gain	—	300,000	—	
Common Mode Rejection Ratio	—	100	—	dB
Power Supply Rejection	—	10	—	μV/V
Unity Gain Bandwidth	—	3	—	MHz
Slew Rate	—	±1	—	V/μs
POWER SUPPLY REQUIREMENTS				
Voltage, rated performance	—	±15	—	Volts
Voltage Range, operating	±5	—	±18	Volts
Quiescent Current	—	—	±11.5	mA
PHYSICAL/ENVIRONMENTAL				
Operating Temperature Range				
FLT-U2		0 to +70°C		
FLT-U2-M		–55 to +125°C		
Storage Temperature Range		–55 to +125°C		
Package		Ceramic 16-pin DIP (double spaced)		

Footnote:

① $f_0 Q = 5 \times 10^5$ optimally.

TECHNICAL NOTES

1. The FLT-U2 has simultaneous lowpass, bandpass and highpass transfer functions. The chosen output for a particular function will be at unity gain based on Tables II and III. This means that the other two unused outputs will be at other gain levels. The gain of the lowpass output is always 10dB higher than the gain of the bandpass output and 20dB higher than the gain of the highpass output.
2. When tuning the filter and checking it over its frequency range, the outputs should be checked with a scope to make sure there is no waveform clipping present, as this will affect the operation of the filter. In particular, the lowpass output should be checked since its gain is the highest.
3. Check f_1, the center frequency for bandpass and the cutoff frequency for lowpass or highpass, at the bandpass output (pin 13). Here the peaking frequency can easily be determined for high-Q filters and the 0° or 180° phase frequency can easily be determined for low-Q filters (depending on whether inverting or noninverting).
4. Tuning resistors should be 1% metal-film types with 100ppm/°C temperature stability or better for best performance. Likewise, external tuning capacitors should be NPO ceramic or other stable capacitor types.

THEORY OF OPERATION

The FLT-U2 block diagram is shown in Figure 2. This is a second-order state-variable filter using three operational amplifiers. Lowpass, bandpass and highpass transfer functions are simultaneously produced at its three output terminals. These three transfer functions are characterized by the following second order equations:

$$H(S) = \frac{K_1}{S^2 + \frac{\omega_0}{Q} S + \omega_0^2} \quad \text{LOWPASS} \qquad \frac{\omega_0}{Q}$$

$$H(S) = \frac{K_2 S}{S^2 + \frac{\omega_0}{Q} S + \omega_0^2} \quad \text{BANDPASS}$$

$$H(S) = \frac{K_3 S^2}{S^2 + \frac{\omega_0}{Q} S + \omega_0^2} \quad \text{HIGHPASS}$$

where K_1, K_2 and K_3 are arbitrary gain constants.

A second-order system is characterized by the location of its poles in the s-plane as shown in Figure 3. The natural radian frequency of this system is ω_0. In Hertz this is $f_0 = \frac{\omega_0}{2\pi}$.

The resonant radian frequency of the circuit is different from the natural radian frequency and is:

$$\omega_1 = \omega_0 \sin\theta = \sqrt{\omega_0^2 - \sigma_1^2}$$

The damping factor d determines the amount of peaking in the filter frequency response and is defined as:

$$d = \cos\theta$$

The point at which the peaking becomes zero is called critical damping and is $d = \sqrt{2}/2$.

Q is found from d and is a measure of the sharpness of the resonance of the peaking:

$$Q = \frac{1}{2d}$$

$$\text{Also, } Q = \frac{f_0}{-3\text{dB Bandwidth}} = \frac{\omega_0}{2\sigma_1}$$

For high-Q filters, the natural frequency and resonant frequency are approximately equal.

$$\omega_1 \approx \omega_0 \quad \text{or} \quad f_1 \approx f_0$$

This is true since $\omega_1 = \omega_0 \sin\theta$ and $\sin\theta \approx 1$ as the poles move close to the j_ω axis in the s-plane.

For high Q's ($Q > 1$), we therefore have for the second order filter:

$f_0 \approx$ Bandpass center frequency
$\approx$ Lowpass corner frequency
$\approx$ Highpass corner frequency

In the simplified tuning procedure which follows, the tuning is accomplished by independently setting the natural frequency and Q of the filter. This is done most simply by assuming unity gain for the output of the desired filter function. Unity gain means a gain of one (±) at dc for lowpass, at center frequency for bandpass, and at high frequency ($f >> f_0$) for highpass. Unity gain does not apply to all outputs simultaneously but only to the chosen output based on the component values given in the tables. Figure 4 shows the relative gains of the three simultaneous outputs assuming the bandpass gain is set to unity. Note that lowpass gain is always 10dB higher than bandpass gain, and highpass gain is always 10dB lower than bandpass gain.

SIMPLIFIED TUNING PROCEDURE

1. Select the desired transfer function (lowpass, bandpass or highpass) and inverted or noninverted output. From this determine the filter configuration (inverting or noninverting) using Table 1.

2. Starting with the desired natural frequency and Q (determined from the filter transfer function or s-plane diagram), compute f_0Q. For $f_0Q > 10^4$, the actual realized Q will exceed the calculated value. At $f_0Q = 10^4$, the increase is about 1%, and at $f_0Q = 10^5$ it is about 20%.

3. **Inverting Configuration.** Using the value of Q from Step 2, find R_1 and R_3 from Table II. R_2 is open, or infinite.

4. **Noninverting Configuration.** Using the value of Q from Step 2, find R_2 and R_3 from Table III. R_1 is open, or infinite.

5. Using the value of f_0 from Step 2, set the natural frequency of the filter by finding R_4 and R_5 from the equation:

$$R_4 = R_5 = \frac{5.03 \times 10^7}{f_0}$$

where R_4 and R_5 are in Ohms and f_0 is in Hertz. The natural frequency varies as $\sqrt{R_4R_5}$ and therefore one value may be increased and the other decreased and the natural frequency will be constant if the geometric mean is constant. To maintain constant bandwidth at the bandpass output while varying center frequency, fix R_4 and vary R_5.

6. For $f_0 < 50$Hz, the internal 1000pF capacitors should be shunted with external capacitors across pins 5 & 7 and 13 & 14. If equal value capacitors are used, R_4 and R_5 are then computed from:

$$R_4 = R_5 = \frac{5.03 \times 10^{10}}{f_0 C} \quad \text{(C in pF)}$$

For unequal value capacitors this becomes:

$$R_4 = R_5 = \frac{5.03 \times 10^{10}}{f_0\sqrt{C_1C_2}} \quad \text{(}C_1\text{ and }C_2\text{ in pF)}$$

In both cases, the capacitance is the sum of the external values and the internal 1000pF values.

Table I. Filter Configuration

	LP	BP	HP
Inverting Input	Inverting	Non-Inv.	Inverting
Noninverting Input	Non-Inv.	Inverting	Non-Inv.

Table II. Inverting Configuration

	R_1	R_2	R_3
Lowpass	100k	Open	$\frac{100k}{3.8Q - 1}$
Bandpass	Q x 31.6k	Open	$\frac{100k}{3.48Q}$
Highpass	10k	Open	$\frac{100k}{6.64Q - 1}$

Table III. Noninverting Configuration

	R_1	R_2	R_3
Lowpass	Open	$\frac{316k}{Q}$	$\frac{100k}{3.16Q - 1}$
Bandpass	Open	100k	$\frac{100k}{3.48Q - 1}$
Highpass	Open	$\frac{31.6k}{Q}$	$\frac{100k}{0.316Q - 1}$

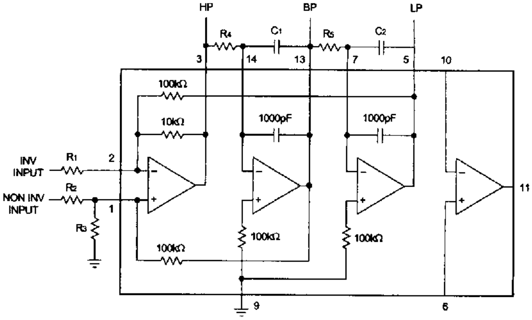


Figure 2. FLT-U2 Block Diagram

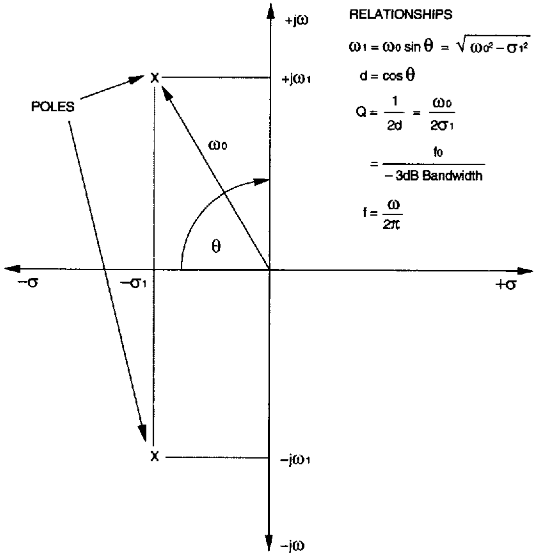


Figure 3. S-Plane Diagram

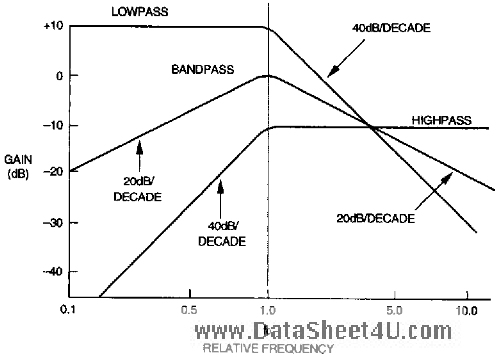


Figure 4. Relative Gains of Simultaneous Outputs, Q = 1

SIMPLIFIED TUNING PROCEDURE (continued)

7. This procedure is based on unity gain output for the desired function. For additional gain, the fourth (uncommitted) operational amplifier should be used as an inverting or noninverting gain stage following the selected output. See Figure 5. A third pole on the real axis of the s-plane may also be added to the transfer function by adding a capacitor to the gain stage as shown in Figure 6.

FILTER DESIGN EXAMPLES

Bandpass Filter with 1kHz Center Frequency Q = 10 and Inverted Output

1. From Table I, the noninverting configuration is chosen to realize an inverted bandpass output $f_0Q = 10^4$ which means the realized Q will be about 1% higher than calculated.
2. From Table III, using Q = 10, we find:

$$R_1 = \text{open}$$

$$R_2 = 100k\Omega$$

$$R_3 = \frac{100k\Omega}{3.48Q - 1} = \frac{100k\Omega}{33.8} = 2.96k\Omega$$

3. Using f_0 of 1kHz, R_4 and R_5 are found from the equation:

$$R_4 = R_5 = \frac{5.03 \times 10^7}{1000} = 50.3k\Omega$$

4. This completes the filter design which is shown in Figure 7. To choose the nearest 1% standard value resistors either 49.9k or 51.1k Ohms could be used; likewise one value of 49.9k and one of 51.1k could be used giving the geometric mean of $\sqrt{R_4R_5} = \sqrt{49.9k \times 51.1k} = 50.5k$ which is even closer. But due to the filter ±5% frequency tolerance, it may be better to hold R_4 constant while varying R_5 to tune it exactly.

Three-Pole Noninverting Butterworth Lowpass Filter with dc Gain of 10 and Cutoff Frequency of 5kHz

The s-plane diagram of the 3-pole Butterworth filter is shown in Figure 8. We will use a second-order filter to realize the two complex conjugate poles and the uncommitted operational amplifier to provide the third real axis pole and a dc gain of 10.

1. From Table I, the noninverting filter configuration would normally be used to give a noninverting lowpass output. In this case, however, we choose an inverting uncommitted op amp with a gain of 10 and therefore we use the inverting configuration for the filter. By comparing the second-order portion of the Butterworth function $S^2 + \omega_0 S = \omega_0^2$ to the standard second-order function $S^2 + \omega_0 S = \omega_0^2$ we find Q = 1. f_0Q is then 5×10^3 so that Q will not exceed its specified value.
2. From Table II, using Q = 1, we find:

$$R_1 = 100k\Omega$$

$$R_2 = \text{open}$$

$$R_3 = \frac{100k}{3.80Q - 1} = 35.7k\Omega$$

3. Using f_0 of 5kHz, R_4 and R_5 are found from the equation:

$$R_4 = R_5 = \frac{5.03 \times 10^7}{5000} = 10.1k\Omega$$

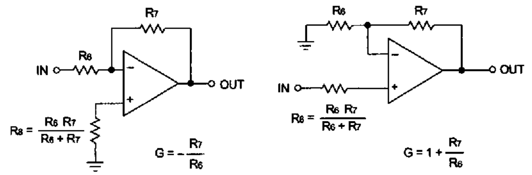


Figure 5. Uncommitted Op Amp Gain Configurations

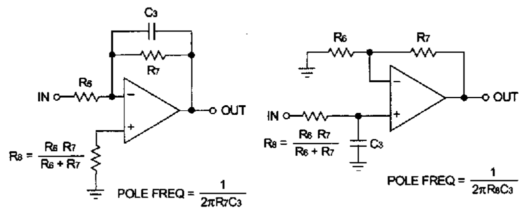


Figure 6. Using the Uncommitted Op Amp to Add a Real Axis Pole

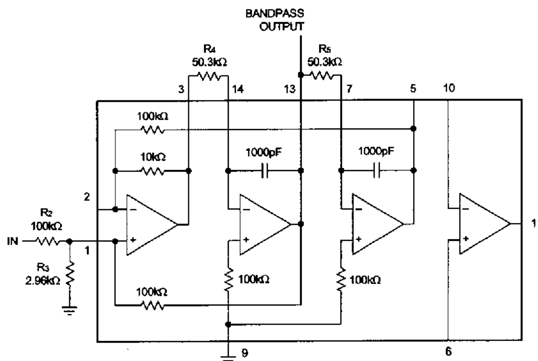


Figure 7. Bandpass Filter Example

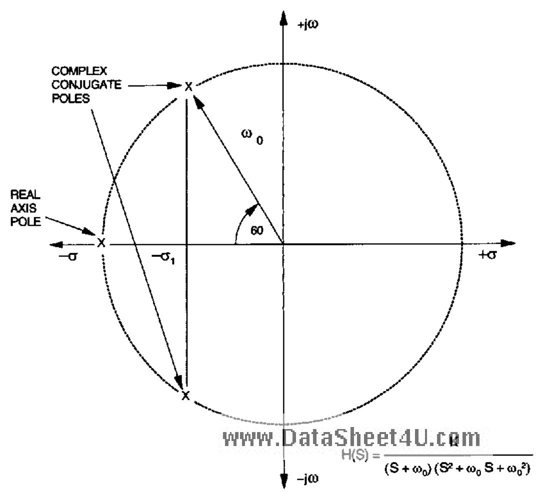


Figure 8. S-Plane diagram of 3-Pole Butterworth Lowpass Filter

FILTER DESIGN EXAMPLES (continued)

4. For the uncommitted output amplifier, a gain of –10 is required. This defines $R_7/R_6 = 10$ and we arbitrarily choose $R_6 = 2k$, $R_7 = 20k\Omega$. R_8 becomes approximately $2k\Omega$.
5. The final step is to realize the real axis pole of the Butterworth filter. This pole is at 5kHz and is set by using capacitor C_3 across the feedback resistor R_7:

$$C_3 = \frac{1}{2\pi f R_7} = \frac{1}{6.28 \times 5 \times 10^3 \times 20 \times 10^3} = 1590\text{pF}$$

6. This completes the 3-pole Butterworth filter which is shown in Figure 9.

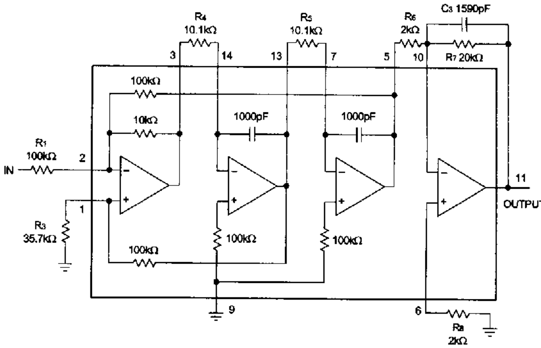


Figure 9. Three-Pole Butterworth Lowpass Filter Example

Highpass Filter with Gain of –1, 20kHz Cutoff Frequency, and Critical Damping

1. From Table I, the inverting configuration must be used to realize a highpass gain of –1. An s-plane diagram of this function is shown in Figure 10. Critical damping requires the pole positions to be on a line 45° with respect to the real axis and this results in no frequency peaking. The damping factor d is:

$$d = \cos\theta = \cos 45° = 0.707$$

and $$Q = \frac{1}{2d} = \frac{1}{2(0.707)} = 0.707$$

Because this is a low-Q system, the natural frequency will not be the same as the highpass cutoff frequency f_1. From Figure 10:

$$f_0 = \frac{f_1}{\cos\theta} = \frac{20\text{kHz}}{(0.707)} = 28.3\text{kHz}$$

Then $f_0Q = 0.707 \times 28.3 \times 10^3 = 2 \times 10^4$, and the Q will exceed its desired value by slightly more than 1%.

2. From Table II, using Q = 0.707 we find:

$$R_1 = 10k\Omega$$

$$R_2 = \text{open}$$

$$R_3 = \frac{100k\Omega}{6.64Q - 1} = \frac{100k\Omega}{3.69} = 27.1k\Omega$$

3. Using $f_0 = 28.3$kHz, R_4 and R_5 are found from the equation:

$$R_4 = R_5 = \frac{5.03 \times 10^7}{28.3 \times 10^3} = 1.78k\Omega$$

4. This completes the highpass filter design which is shown in Figure 11. When using this filter, care should be exercised so that clipping does not occur due to excessive input levels. If clipping occurs, the filter will not operate properly. Clipping will first occur at the lowpass output around f_0 since its gain is 20dB higher than the highpass output. The signal level should be reduced so that clipping does not occur anywhere in the frequency range used. If a higher signal level is required, the highpass output should be amplified by a gain stage using the uncommitted operational amplifier.

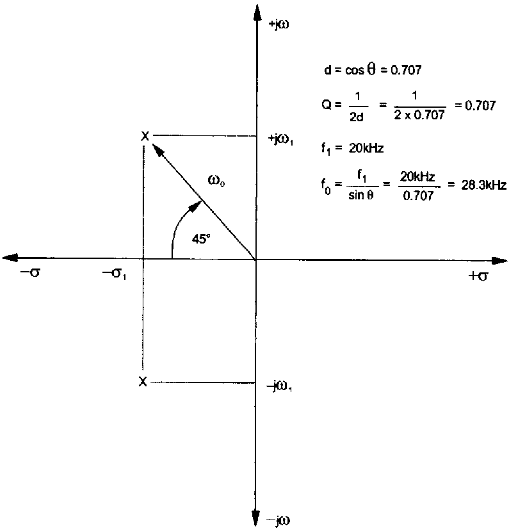


Figure 10. S-Plane Diagram of Highpass Filter with Critical Damping

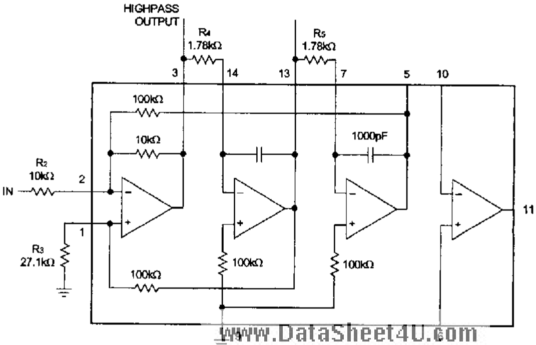


Figure 11. Highpass Filter Example

ADVANCED FILTERS

All of the common filter types can be realized using cascaded FLT-U2 stages. This includes multi-pole Butterworth, Bessel, Chebyshev and Elliptic types. The basic procedure is to implement each pole pair with a single FLT-U2 and cascade enough units to realize all poles. A real-axis pole is implemented by an uncommitted operational amplifier stage. Each stage should be separately tuned with an oscillator and scope and then the stages connected together and checked. See Figure 12.

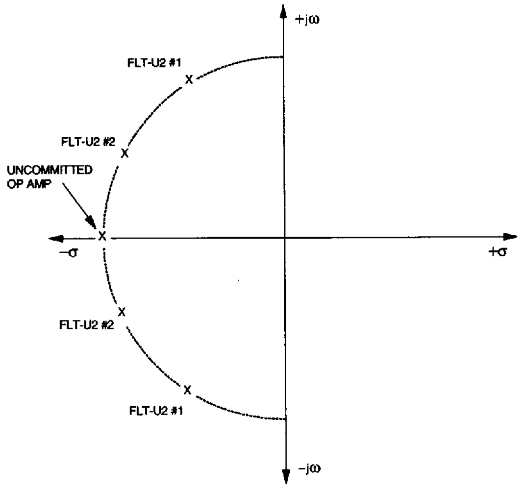
A notch filter can be constructed in several ways. The first way is to use the FLT-U2 as an inverting bandpass filter and sum the output of the filter with the input signal by means of the uncommitted operational amplifier. This produces a net subtraction at the center frequency of the bandpass which produces a null at the output of the amplifier. See Figure 13. Likewise, lowpass and highpass outputs (which are always in phase) can be combined with each other through an external operational amplifier. The highpass output must have some gain added to it, however, so that its gain is equal to that of the lowpass output. A third method is to use two separate FLT-U2s, one as a two-pole lowpass filter and the other as a two-pole highpass filter. Again, the outputs are combined through an operational amplifier. This method permits independent tuning of the two sections to get the best null response.

Further discussion of filter designs is beyond the scope of this data sheet and the user is referred to the various texts on filter design, some of which are listed below.

Estep, G.J., *The State Variable Active Filter Configuration Handbook*, 2nd Edition, Agoura, CA., 1974.

Reference Data for Radio Engineers, Howard W. Sams & Co., Inc., 5th Edition.

Christian, E. and Eisenmann, E., *Filter Design Tables and Graphs,* McGraw-Hill Book Co., 1974.



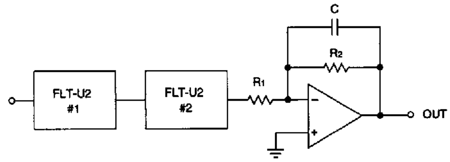


Figure 12. Realization of a Complex Multi-Pole Filter

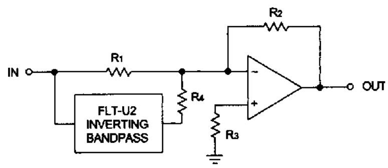
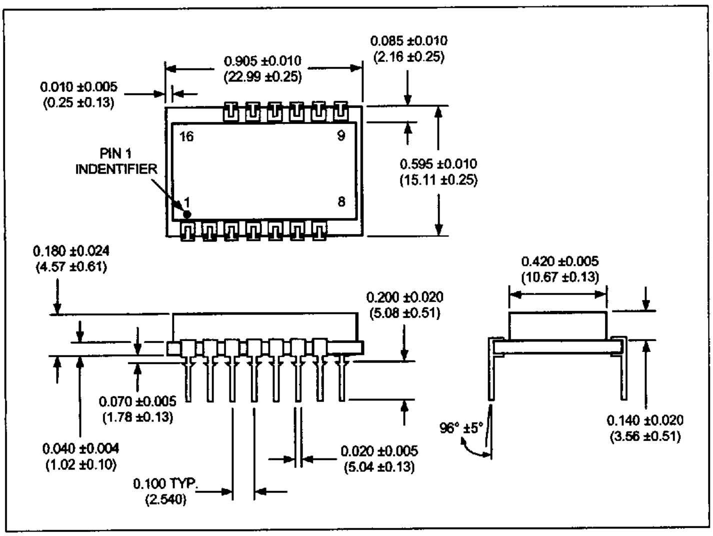


Figure 13. Realization of a Notch Filter

MECHANICAL DIMENSIONS INCHES (mm)



ORDERING INFORMATION

MODEL	OPERATING TEMP. RANGE
FLT-U2	0 to +70°C
FLT-U2-M	–55 to +125°C