

AF100 Universal Active Filter

General Description

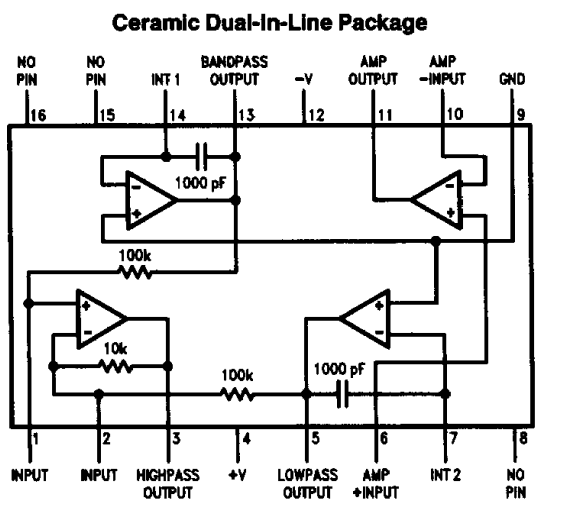
The AF100 state variable active filter is a general second order lumped RC network. Only four external resistors program the AF100 for specific second order functions. Lowpass, highpass, and bandpass functions are available simultaneously at separate outputs. Notch and allpass functions are available by summing the outputs in the uncommitted output summing amplifier. Higher order systems are realized by cascading AF100 active filters with appropriate programming resistors.

Any of the classical filter configurations, such as Butterworth, Bessel, Cauer, and Chebyshev can be formed.

Features

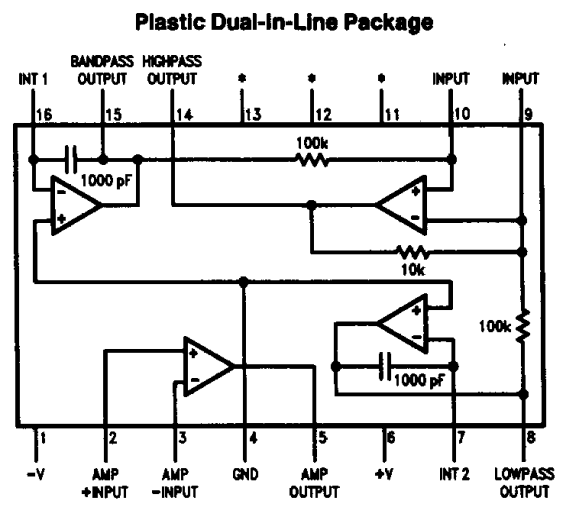
- Military or commercial specifications
- Independent Q, frequency, gain adjustments
- Low sensitivity to external component variation
- Separate lowpass, highpass, bandpass outputs
- Inputs may be differential, inverting, or non-inverting
- Allpass and notch outputs may be formed using uncommitted amplifier
- Operates to 10 kHz
- Q range to 500
- Power supply range ±5V to ±18V
- Frequency accuracy ±1% unadjusted
- Q frequency product $\leq 50,000$

Connection Diagrams



Top View

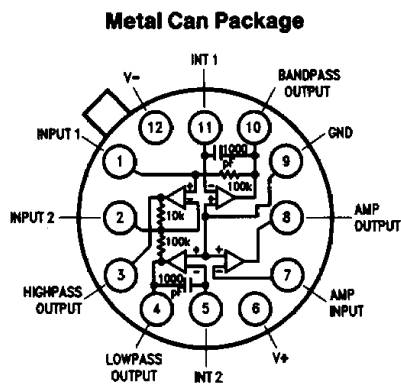
Order Number AF100-1CJ or AF100-2CJ
See NS Package Number HY13A



*Note: Internally connected. Do not use.

Top View

Order Number AF100-1CN or AF100-2CN
See NS Package Number N16A



Top View

Order Number AF100-1CJ, AF100-1G, AF100-2CG or AF100-2G
See NS Package Number H12B

Absolute Maximum Ratings

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

| | |
|--|--------------------------------|
| Supply Voltage | ± 18V |
| Power Dissipation | 900 mW/Package (500 mW/Amp) |
| Differential Input Voltage | ± 36V |
| Output Short Circuit Duration (Note 1) | Infinite |
| Lead Temperature (Soldering, 10 sec.) | 300°C |

| | | |
|-----------------------|--|------------------------------------|
| Operating Temperature | AF100-1CJ, AF100-2CJ, AF100-1CG, AF100-2CG, AF100-1CN, AF100-2CN AF100-1G, AF100-2G | -25°C to +85°C -55°C to +125°C |
| Storage Temperature | AF100-1G, AF100-2G AF100-1CG, AF100-2CG, AF100-1CJ, AF100-2CJ, AF100-1CN, AF100-2CN | -65°C to +125°C -25°C to +100°C |

Electrical Characteristics (Complete Active Filter) (Note 2)

| Parameter | Conditions | Min | Typ | Max | Units |
|--|--|-----|-------|----------------|--------|
| Frequency Range | $f_C \times Q \leq 50,000$ | | | 10k | Hz |
| Q Range | $f_C \times Q \leq 50,000$ | | | 500 | Hz/Hz |
| f_0 Accuracy AF100-1, AF100-1C AF100-2, AF100-2C | $f_C \times Q \leq 10,000, T_A = 25^\circ\text{C}$ $f_C \times Q \leq 10,000, T_A = 25^\circ\text{C}$ | | | ± 2.5 ± 1.0 | % |
| f_0 Temperature Coefficient | | | ± 50 | ± 150 | ppm/°C |
| Q Accuracy | $f_C \times Q \leq 10,000, T_A = 25^\circ\text{C}$ | | | ± 7.5 | % |
| Q Temperature Coefficient | | | ± 300 | ± 750 | ppm/°C |
| Power Supply Current | $V_S = \pm 15V$ | | 2.5 | 4.5 | mA |

Electrical Characteristics (Internal Op Amp) (Note 3)

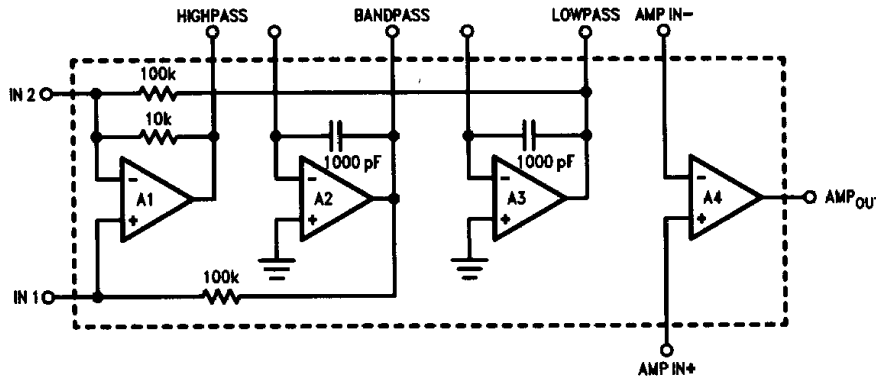
| Parameter | Conditions | Min | Typ | Max | Units |
|--------------------------------|---|--------------|--------------|-----|------------------|
| Input Offset Voltage | $R_S \leq 10\text{ k}\Omega$ | | 1.0 | 6.0 | mV |
| Input Offset Current | | | 4 | 50 | nA |
| Input Bias Current | | | 30 | 200 | nA |
| Input Resistance | | | 2.5 | | M Ω |
| Large Signal Voltage Gain | $R_L \geq 2\text{ k}$ $V_{OUT} = \pm 10V$ | 25 | 160 | | V/mV |
| Output Voltage Swing | $R_L = 10\text{ k}\Omega$ $R_L = 2\text{ k}\Omega$ | ± 12 ± 10 | ± 14 ± 13 | | V |
| Input Voltage Range | | ± 12 | | | V |
| Common Mode Rejection Ratio | $R_S \leq 10\text{ k}\Omega$ | 70 | 90 | | dB |
| Supply Voltage Rejection Ratio | $R_S \leq 10\text{ k}\Omega$ | 77 | 96 | | dB |
| Output Short Circuit Current | | | 25 | | mA |
| Slew Rate (Unity Gain) | | | 0.6 | | V/ μs |
| Small Signal Bandwidth | | | 1 | | MHz |
| Phase Margin | | | 60 | | Degrees |

Note 1: Any of the amplifiers can be shorted to ground indefinitely, however more than one should not be simultaneously shorted as the maximum junction temperature will be exceeded.

Note 2: Specifications apply for $V_S = \pm 15V$, over -25°C to +85°C for the AF100-1C and AF100-2C and over -55°C to +125°C for the AF100-1 and AF100-2, unless otherwise specified.

Note 3: Specifications apply for $V_S = \pm 15V, T_A = 25^\circ\text{C}$.

Application Information



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FIGURE 1. AF100 Schematic

CIRCUIT DESCRIPTION AND OPERATION

A schematic of the AF100 is shown in Figure 1. Amplifier A1 is a summing amplifier with inputs from integrator A2 to the non-inverting input and integrator A3 to the inverting input. Amplifier A4 is an uncommitted amplifier.

By adding external resistors the circuit can be used to generate the second order system

$$T(s) = \frac{a_3 s^2 + a_2 s + a_1}{s^2 + b_2 s + b_1}$$

The denominator coefficients determine the complex pole pair location and the quality of the poles where

$$\omega_0 = \sqrt{b_1} = \text{the radian center frequency}$$

$$Q = \frac{\omega_0}{b_2} = \text{the quality of the complex pole pair}$$

If the output is taken from the output of A1, numerator coefficients a_1 and a_2 equal zero, and the transfer function becomes:

$$T(s) = \frac{a_3 s^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \quad (\text{highpass})$$

If the output is taken from the output of A2, numerator coefficients a_1 and a_3 equal zero and the transfer function becomes:

$$T(s) = \frac{a_2 s}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \quad (\text{bandpass})$$

If the output is taken from the output of A3, numerator coefficients a_3 and a_2 equal zero and the transfer function becomes:

$$T(s) = \frac{a_1}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \quad (\text{lowpass})$$

Using proper input and output connections the circuit can also be used to generate the transfer functions for a notch and allpass filter.

In the transfer function for a notch function a_2 becomes zero, a_1 equals 1, and a_3 equals ω_0^2 . The transfer function becomes:

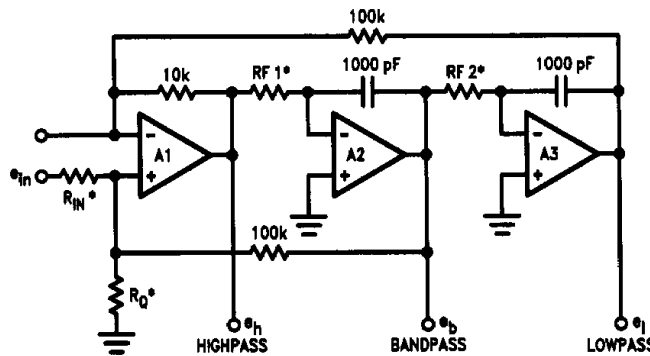
$$T(s) = \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \quad (\text{notch})$$

In the allpass transfer function $a_1 = 1$, $a_2 = -\omega_0/Q$ and $a_3 = \omega_0^2$. The transfer function becomes:

$$T(s) = \frac{s^2 - \frac{\omega_0}{Q} s + \omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \quad (\text{allpass})$$

COMMON CONFIGURATIONS

The specific transfer functions for some of the most useful circuit configurations using the AF100 are illustrated in Figures 2 through 8. Also included are the gain equations for each transfer function in the frequency band of interest, the Q equation, center frequency equation and the Q determining resistor equation.



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*External components

FIGURE 2. Non-Inverting Input ($Q > Q_{MIN}$, see Q Tuning Section)

1

Applications Information (Continued)

a) Non-inverting input (Figure 2) transfer equations are:

$$\frac{e_h}{e_{IN}} = \frac{s^2 \left[\frac{1.1}{1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ}} \right]}{\Delta} \quad (\text{highpass})$$

$$\frac{e_b}{e_{IN}} = \frac{-s \omega_1 \left[\frac{1.1}{1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ}} \right]}{\Delta} \quad (\text{bandpass})$$

$$\frac{e_l}{e_{IN}} = \frac{\omega_1 \omega_2 \left[\frac{1.1}{1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ}} \right]}{\Delta} \quad (\text{lowpass})$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}}$$

where

$$\Delta = s^2 + s \left[\frac{1.1}{1 + \frac{10^5}{RQ} + \frac{10^5}{R_{IN}}} \right] \omega_1 + 0.1 \omega_1 \omega_2$$

$$\left. \frac{e_l}{e_{IN}} \right|_{s \rightarrow 0} = \frac{1.1}{\left(1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ} \right)}$$

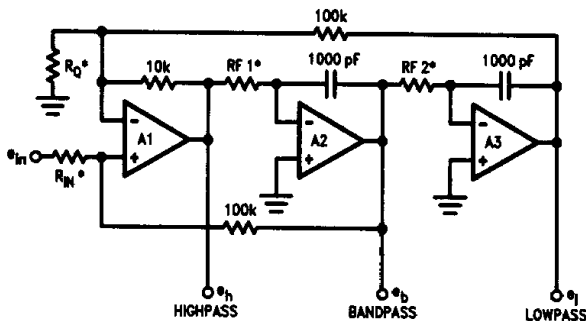
$$\left. \frac{e_h}{e_{IN}} \right|_{s \rightarrow \infty} = \frac{1.1}{\left(1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ} \right)}$$

$$\left. \frac{e_b}{e_{IN}} \right|_{\omega = \omega_0} = - \frac{\left(1 + \frac{10^5}{RQ} + \frac{10^5}{R_{IN}} \right)}{\left(1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ} \right)}$$

$$\omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$Q = \left(\frac{1 + \frac{10^5}{R_{IN}} + \frac{10^5}{RQ}}{1.1} \right) \sqrt{0.1 \left(\frac{\omega_2}{\omega_1} \right)}$$

$$RQ = \frac{10^5}{\left(\frac{1.1Q}{\sqrt{0.1 \frac{\omega_2}{\omega_1}}} \right) - 1 - \frac{10^5}{R_{IN}}}$$



*External components

FIGURE 3. Non-Inverting Input
($Q < Q_{MIN}$, see Q Tuning Section)

b) Non-inverting input (Figure 3) transfer equations are:

$$\frac{e_h}{e_{IN}} = \frac{s^2 \left[\frac{1.1 + \frac{10^4}{RQ}}{1 + \frac{R_{IN}}{10^5}} \right]}{\Delta} \quad (\text{highpass})$$

$$\frac{e_b}{e_{IN}} = \frac{-s \omega_1 \left[\frac{1.1 + \frac{10^4}{RQ}}{1 + \frac{R_{IN}}{10^5}} \right]}{\Delta} \quad (\text{bandpass})$$

$$\frac{e_l}{e_{IN}} = \frac{\omega_1 \omega_2 \left[\frac{1.1 + \frac{10^4}{RQ}}{1 + \frac{R_{IN}}{10^5}} \right]}{\Delta} \quad (\text{lowpass})$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}}$$

where

$$\Delta = s^2 + s \omega_1 \left[\frac{1.1 + \frac{10^4}{RQ}}{1 + \frac{10^5}{R_{IN}}} \right] + 0.1 \omega_1 \omega_2$$

$$\left. \frac{e_l}{e_{IN}} \right|_{s \rightarrow 0} = \frac{1.1 + \frac{10^4}{RQ}}{0.1 \left(1 + \frac{R_{IN}}{10^5} \right)}$$

$$\left. \frac{e_h}{e_{IN}} \right|_{s \rightarrow \infty} = \frac{1.1 + \frac{10^4}{RQ}}{1 + \frac{R_{IN}}{10^5}}$$

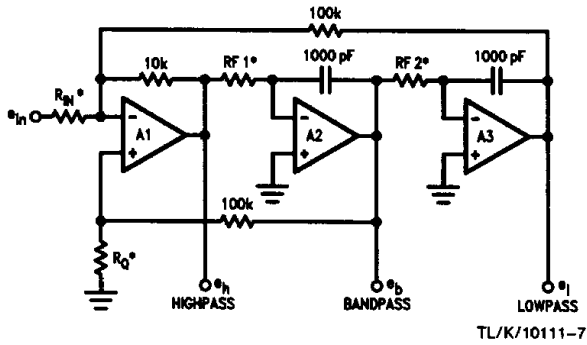
$$\left. \frac{e_b}{e_{IN}} \right|_{\omega = \omega_0} = - \frac{1 + \frac{10^4}{R_{IN}}}{1 + \frac{R_{IN}}{10^5}}$$

$$\omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$Q = \left[\frac{1 + \frac{10^5}{R_{IN}}}{1.1 + \frac{10^4}{RQ}} \right] \sqrt{0.1 \frac{\omega_2}{\omega_1}}$$

$$RQ = \frac{10^4}{\left(1 + \frac{10^5}{R_{IN}} \right) \left(\frac{\sqrt{0.1 \frac{\omega_2}{\omega_1}}}{Q} \right) - 1.1}$$

Applications Information (Continued)



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*External components

FIGURE 4. Inverting Input

c) Inverting input (Figure 4) transfer function equations are:

$$\frac{e_h}{e_{IN}} = \frac{-s^2 \frac{10^4}{R_{IN}}}{\Delta} \quad (\text{highpass})$$

$$\frac{e_b}{e_{IN}} = \frac{s \omega_1 \frac{10^4}{R_{IN}}}{\Delta} \quad (\text{bandpass})$$

$$\frac{e_l}{e_{IN}} = \frac{-\omega_1 \omega_2 \frac{10^4}{R_{IN}}}{\Delta} \quad (\text{lowpass})$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}}$$

where

$$\Delta = s^2 + s \omega_1 \left[\frac{1.1 + \frac{10^4}{R_{IN}}}{1 + \frac{10^5}{R_Q}} \right] + 0.1 \omega_1 \omega_2$$

$$\left. \frac{e_l}{e_{IN}} \right|_{s \rightarrow 0} = -\frac{10^5}{R_{IN}} \quad (\text{lowpass})$$

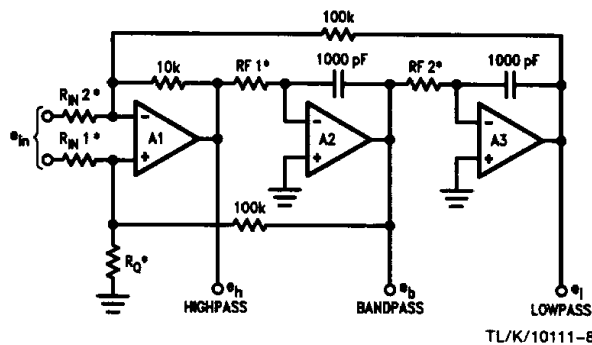
$$\left. \frac{e_h}{e_{IN}} \right|_{s \rightarrow \infty} = -\frac{10^4}{R_{IN}} \quad (\text{highpass})$$

$$\left. \frac{e_b}{e_{IN}} \right|_{\omega = \omega_0} = \frac{\frac{10^4}{R_{IN}} \left(1 + \frac{10^5}{R_Q} \right)}{1.1 + \frac{10^4}{R_{IN}}} \quad (\text{bandpass})$$

$$\omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$Q = \left[\frac{1 + \frac{10^5}{R_Q}}{1.1 + \frac{10^4}{R_{IN}}} \right] \sqrt{0.1 \frac{\omega_2}{\omega_1}}$$

$$RQ = \frac{10^5}{\frac{Q}{\sqrt{0.1 \frac{\omega_2}{\omega_1}}} \left(1.1 + \frac{10^4}{R_{IN}} \right) - 1}$$



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*External components

FIGURE 5. Differential Input

d) Differential input (Figure 5) transfer function equations are:

$$\frac{e_h}{e_{IN}} = \frac{s^2 \frac{10^4}{R_{IN2}}}{\Delta} \quad (\text{highpass})$$

$$\frac{e_b}{e_{IN}} = \frac{-s \omega_1 \frac{10^4}{R_{IN2}}}{\Delta} \quad (\text{bandpass})$$

$$\frac{e_l}{e_{IN}} = \frac{-\omega_1 \omega_2 \frac{10^4}{R_{IN2}}}{\Delta} \quad (\text{lowpass})$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}}$$

where

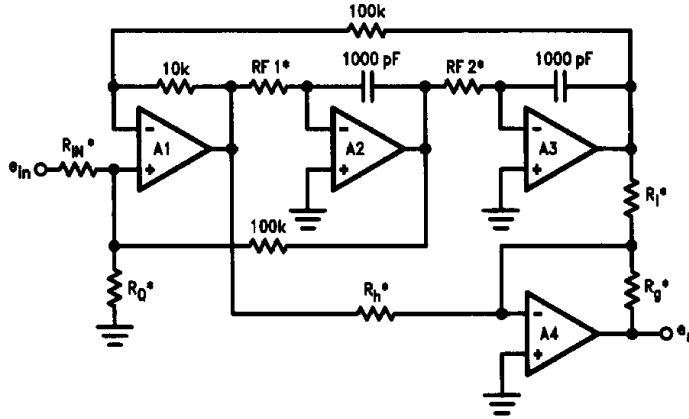
$$\Delta = s^2 + s \omega_1 \left[\frac{1.1 + \frac{10^4}{R_{IN2}}}{1 + \frac{10^5}{R_Q} + \frac{10^5}{R_{IN1}}} \right] + 0.1 \omega_1 \omega_2$$

$$\omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$Q = \left[\frac{1 + \frac{10^5}{R_Q} + \frac{10^5}{R_{IN1}}}{1.1 + \frac{10^4}{R_{IN2}}} \right] \sqrt{0.1 \frac{\omega_2}{\omega_1}}$$

$$RQ = \frac{10^5}{\frac{Q}{\sqrt{0.1 \frac{\omega_2}{\omega_1}}} \left(1.1 + \frac{10^4}{R_{IN2}} \right) - 1 - \frac{10^5}{R_{IN1}}}$$

Applications Information (Continued)



*External components

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FIGURE 6. Output Notch Using All Four Amplifiers

e) Output notch (Figure 6) transfer function equations are:

$$\frac{e_n}{e_{IN}} = \frac{(s^2 + \omega_z^2) \left[\frac{1.1}{1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ}} \right] \frac{R_g}{R_h}}{s^2 + s\omega_1 \left[\frac{1.1}{1 + \frac{10^5}{RQ} + \frac{10^5}{R_{IN}}} \right] + 0.1 \omega_1 \omega_2}$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}} \quad \omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$\omega_z = \omega_0 \sqrt{\frac{10 R_h}{R_l}}$$

$$\left. \frac{e_n}{e_{IN}} \right|_{s \rightarrow 0} = \frac{11}{\left(1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ}\right)} \frac{R_g}{R_l}$$

$$\left. \frac{e_n}{e_{IN}} \right|_{s \rightarrow \infty} = \frac{1.1}{\left(1 + \frac{R_{IN}}{10^5} + \frac{R_{IN}}{RQ}\right)} \frac{R_g}{R_h}$$

$$\left. \frac{e_n}{e_{IN}} \right|_{\omega = \omega_z} = 0$$

f) Input notch (Figure 7) transfer function equations are:

$$\frac{e_n}{e_{IN}} = \frac{\frac{C_z}{10^{-9}} [s^2 + \omega_z^2]}{s^2 + s\omega_1 \left[\frac{1.1 RQ}{10^5 + RQ} \right] + \omega_0^2}$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}}$$

$$\omega_z = \omega_0 \sqrt{\frac{R_{F2} \times 10^{-9}}{R_z C_z}} \quad \omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$\left. \frac{e_n}{e_{IN}} \right|_{\omega \rightarrow 0} = -\frac{R_{F2}}{R_z}$$

$$\left. \frac{e_n}{e_{IN}} \right|_{\omega \rightarrow \infty} = -\frac{C_z}{10^{-9}}$$

g) Allpass (Figure 8) transfer function equations are:

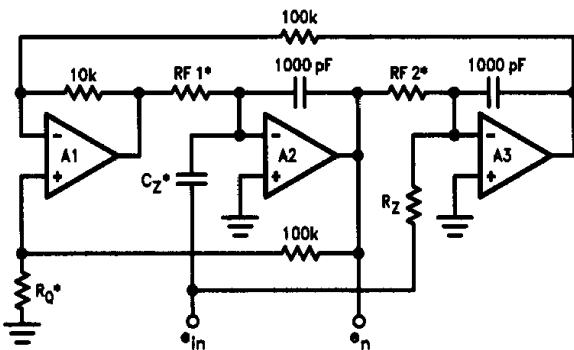
$$\frac{e_o}{e_{IN}} = - \frac{\left[s^2 - s\omega_1 \left[\frac{1.1}{2 + \frac{R_{IN}}{RQ}} \right] + \omega_0^2 \right]}{\left[s^2 + s\omega_1 \left[\frac{1.1}{2 + \frac{R_{IN}}{RQ}} \right] + \omega_0^2 \right]}$$

$$Q = \frac{2 + \frac{10^5}{RQ}}{1.1} \sqrt{0.1 \frac{\omega_2}{\omega_1}}$$

$$\omega_1 = \frac{10^9}{R_{F1}} \quad \omega_2 = \frac{10^9}{R_{F2}}$$

$$\omega_0 = \sqrt{0.1 \omega_1 \omega_2}$$

$$\text{Time delay at } \omega = \frac{2Q}{\omega_0} \text{ seconds}$$

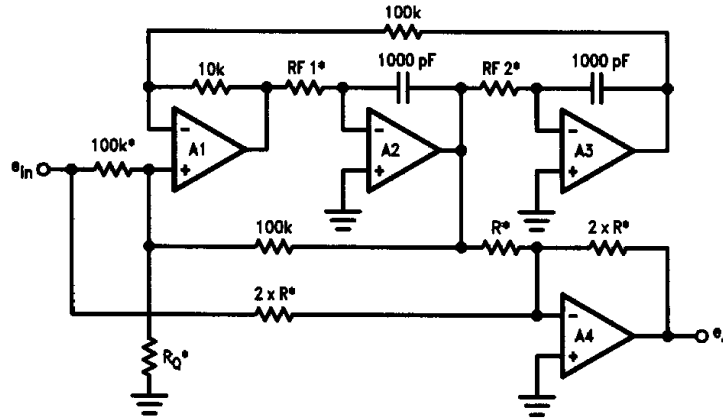


*External components

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FIGURE 7. Input Notch Using Three Amplifiers

Applications Information (Continued)



*External components

FIGURE 8. Allpass

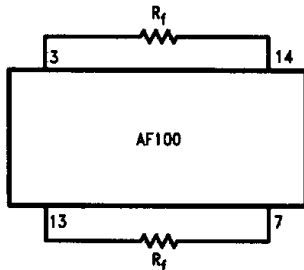
TL/K/10111-11

FREQUENCY TUNING

To tune the AF100 two resistors are required for frequencies between 200 Hz and 10 kHz. For lower frequencies "T" tuning or addition of external capacitors is required. Using external capacitors allows the user to go as low in frequency as he desires. "T" tuning and external capacitors can be used together.

Two resistor tuning for 200 Hz to 10 kHz

$$R_f = \frac{50.33 \times 10^6}{f_0} \Omega$$

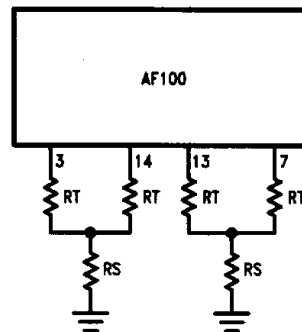


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FIGURE 9. Resistive Tuning

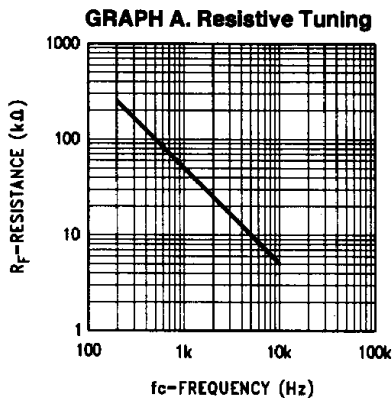
"T" resistive tuning for $f_0 < 200$ Hz

$$R_s = \frac{R_f^2}{R_f - 2R_t} \quad R_t < \frac{R_f}{2}$$

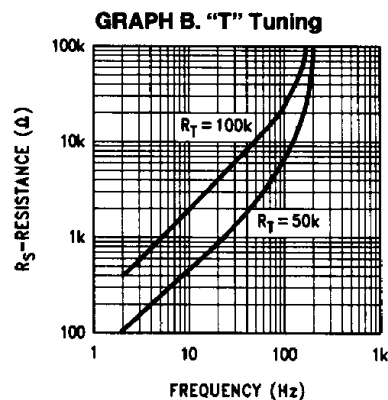


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FIGURE 10. T Tuning



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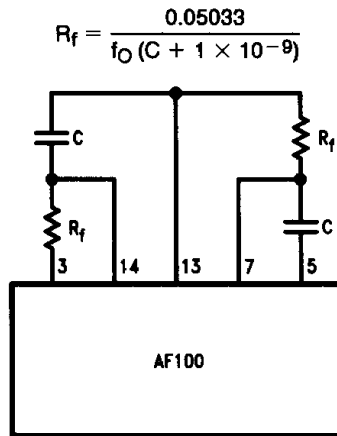


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Applications Information (Continued)

RC tuning for $f_0 < 200$ Hz

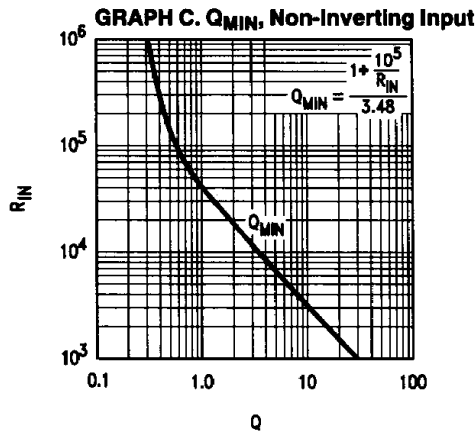


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FIGURE 11. Low Frequency RC Tuning

Q TUNING

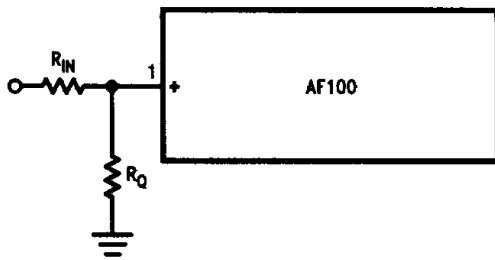
To tune the Q of an AF100 requires one resistor from pins 1 or 2 to ground. The value of the Q tuning resistor depends on the input connection and input resistance as well as the value of the Q. The Q of the unit is inversely proportional to resistance to ground at pin 1 and directly proportional to resistance to ground from pin 2.



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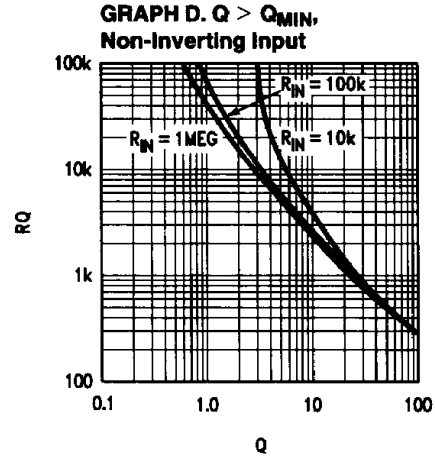
For $Q > Q_{MIN}$ in non-inverting mode:

$$RQ = \frac{10^5}{3.48Q - 1 - \frac{10^5}{R_{IN}}}$$



TL/K/10111-18

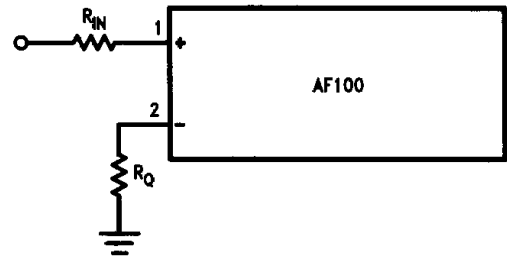
FIGURE 12. Q Tuning for $Q > Q_{MIN}$, Non-Inverting Input



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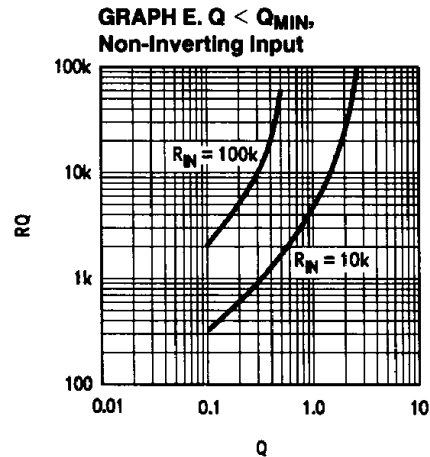
For $Q < Q_{MIN}$ in non-inverting mode:

$$RQ = \frac{10^4}{0.3162 \frac{1 + \frac{10^5}{R_{IN}}}{Q} - 1.1}$$



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FIGURE 13. Q Tuning for $Q < Q_{MIN}$, Non-Inverting Input

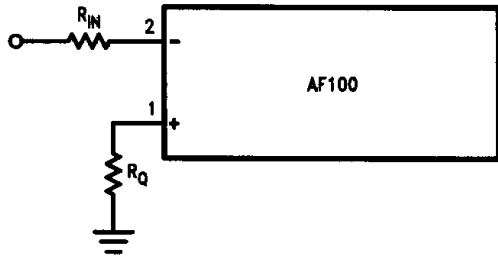


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Applications Information (Continued)

For any Q in inverting mode:

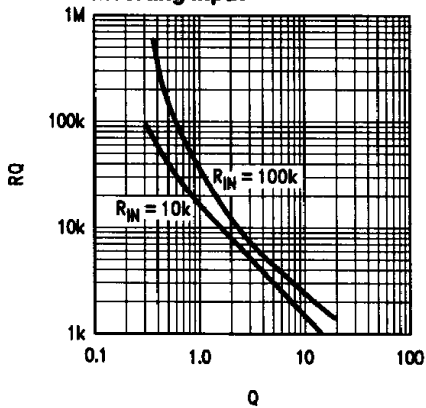
$$RQ = \frac{10^5}{3.16Q \left(1.1 + \frac{10^4}{R_{IN}} \right) - 1}$$



TL/K/10111-22

FIGURE 14. Q Tuning Inverting Input

GRAPH F. Q Tuning Inverting Input



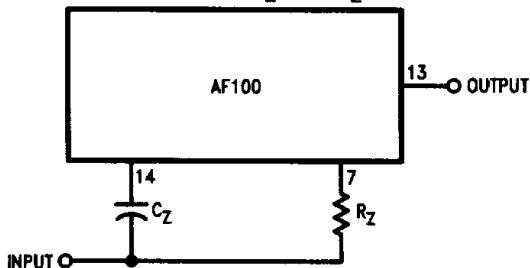
TL/K/10111-23

NOTCH TUNING

Two methods to generate notches are the RC input and lowpass/highpass summing. The RC input method requires adding a capacitor and resistor connected to the two integrator inputs. The capacitor connects to "Int 1" and the resistor connects to "Int 2". The output summing requires two resistors connected to the lowpass and highpass output.

For input RC notch tuning:

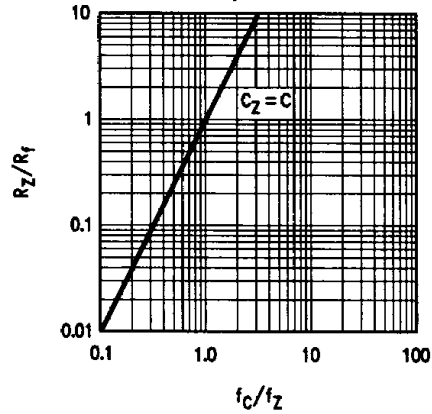
$$R_Z = \frac{R_F \times 10^{-9}}{C_Z} \left(\frac{f_O}{f_Z} \right)^2$$



TL/K/10111-24

FIGURE 15. Input RC Notch

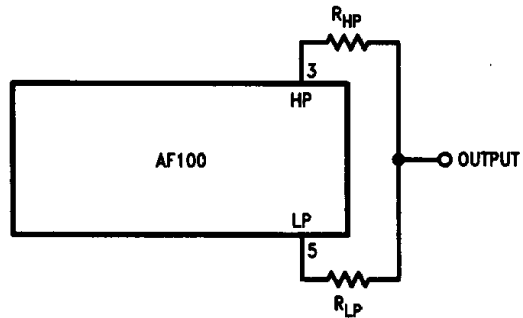
GRAPH G. Input RC Notch



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For output notch tuning:

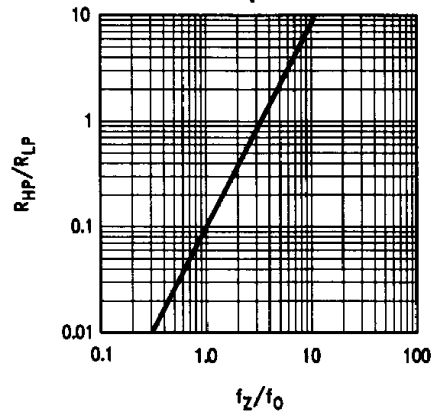
$$R_{HP} = \left(\frac{f_Z}{f_O} \right)^2 \frac{R_{LP}}{10}$$



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FIGURE 16. Output Notch

GRAPH H. Output Notch



TL/K/10111-27

Applications Information (Continued)

TUNING TIPS

In applications where 2% to 3% accuracy is not sufficient to provide the required filter response, the AF100 stages can be tuned by adding trim pots or trim resistors in series or parallel with one of the frequency determining resistors and the Q determining resistor.

When tuning a filter section, no matter what output configuration is to be used in the circuit, measurements are made between the input and the bandpass (pin 13) output.

Before any tuning is attempted the lowpass (pin 7) output should be checked to see that the output is not clipping. At the center frequency of the section the lowpass output is 10 dB higher than the bandpass output and 20 dB higher than the highpass. This should be kept in mind because if clipping occurs the results obtained when tuning will be incorrect.

Frequency Tuning

By adjusting the resistance between pins 7 and 13 the center frequency of a section can be adjusted. If the input is through pin 1 the phase shift at center frequency will be 180° and if the input is through pin 2 the phase shift at center frequency will be 0°. Adjusting center frequency by phase is the most accurate but tuning for maximum gain is also correct.

"Q" Tuning

The "Q" is tuned by adjusting the resistance between pin 1 or 2 and ground. Low Q tuning resistors will be from pin 2 to ground ($Q < 0.6$). High Q tuning resistors will be from pin 1 to ground. To tune the Q correctly the signal source must have an output impedance very much lower than the input resistance of the filter since the input resistance affects the Q. The input must be driven through the same resistance the circuit will see to obtain precise adjustment.

The lower 3 dB (45°) frequency, f_L , and the upper 3 dB (45°) frequency, f_H , can be calculated by the following equations:

$$f_H = \left(\frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1} \right) \times (f_0)$$

where f_0 = center frequency

$$f_L = \left(\sqrt{\left(\frac{1}{2Q}\right)^2 + 1} - \frac{1}{2Q} \right) \times (f_0)$$

When adjusting the Q, set the signal source to either f_H or f_L and adjust for 45° phase change or a 3 dB gain change.

Notch Tuning

If a circuit has a jw axis zero pair the notch can be tuned by adjusting the ratio of the summing resistors (lowpass/highpass summing) or the input resistance (input RC).

In either case the signal is connected to the input and the proper resistor is adjusted for a null at the output.

Special Cases

When using the input RC notch the unit cannot be tuned through the normal input so an additional 100k resistor can be added at pin 1 and the unit can be tuned normally. Then the 100k input resistor should be grounded and the notch tuned through the normal RC input.

An alternative way of tuning is to tune using the Q resistor as the input. This requires the Q resistor be lifted from ground and connecting the signal source to the normally grounded end of the Q resistor. This has the problem that when the Q resistor is grounded after tuning, its value is decreased by the output impedance of the source. This technique has the advantage of not requiring an additional resistor.

TUNING PROCEDURE (See Figure 17)

Center Frequency Tuning

Set oscillator to center frequency desired for the filter section, adjust amplitude and check that clipping does not occur at the lowpass output pin 5 (AF100J).

Adjust the resistance between pins 13 and 7 until the phase shift between input and bandpass output is 180°.

Q Tuning

Set oscillator to upper or lower 45° frequency (see tuning tips) and tune the Q resistor until the phase shift is 135° (upper 45° frequency) or 225° (lower 45° frequency).

Zero Tuning

Set the oscillator output to the zero frequency and tune the zero resistor for a null at the output of the summing amplifier.

Gain Adjust

Set the oscillator to any desired frequency and the gain can be adjusted by measuring the output of the summing amplifier and adjusting the feedback resistance.

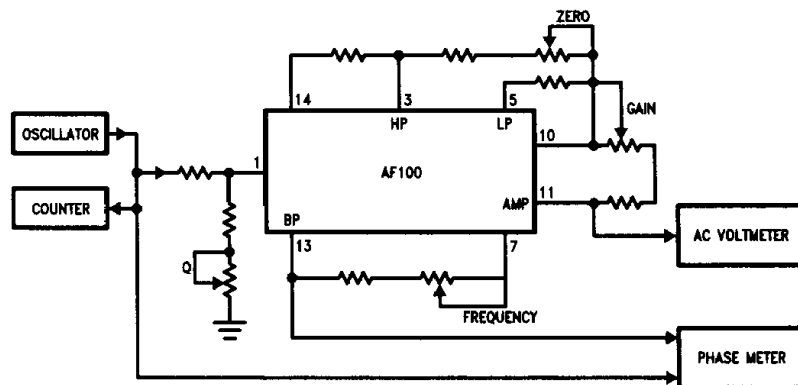
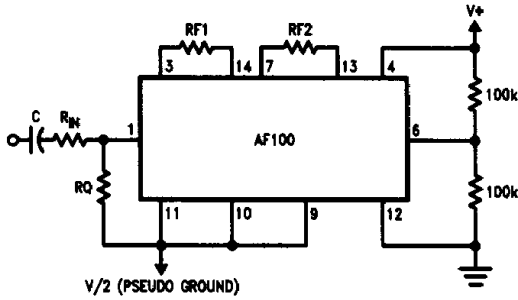


FIGURE 17. Filter Tuning Setup

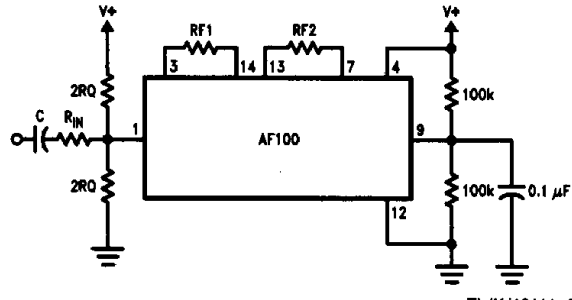
TL/K/10111-28

Applications Information (Continued)



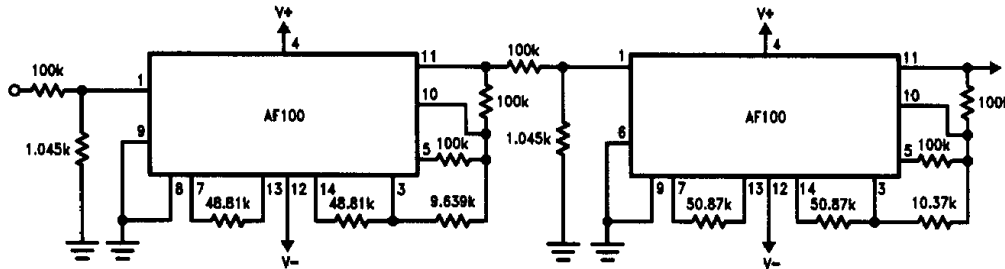
TL/K/10111-29

FIGURE 18. Single Power Supply Connection Using Uncommitted Amplifier to Split Supply



TL/K/10111-30

FIGURE 19. Single Power Supply Connection Using Relative Dividers

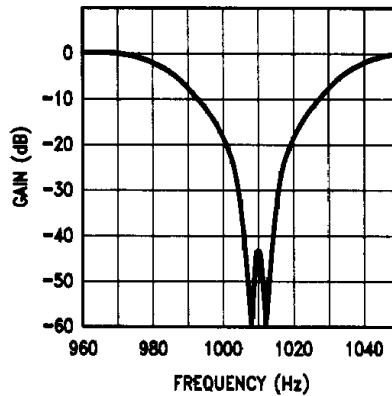


TL/K/10111-31

Performance

- 0.1 dB ripple passband
- 0.1 dB notch width = 100 Hz
- 40 dB notch width = 6.25 Hz

4th Order 1010 Hz Notch



STAGE 1

| |
|---------------------------|
| $F_C = 1031.1 \text{ Hz}$ |
| $Q = 28.34$ |
| $F_Z = 1012.2 \text{ Hz}$ |

STAGE 2

| |
|---------------------------|
| $F_C = 989.3 \text{ Hz}$ |
| $Q = 28.34$ |
| $F_Z = 1007.8 \text{ Hz}$ |

TL/K/10111-32

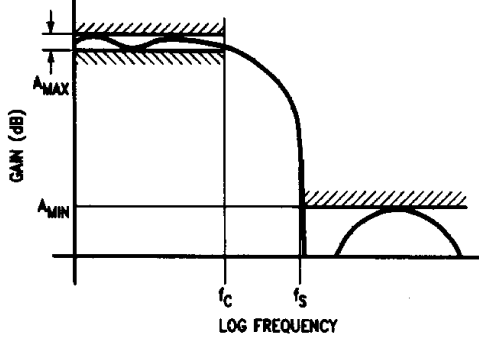
FIGURE 20. 1010 Hz Notch—Telephone Holding Tone Reject Filter

FILTER DESIGN

Since most filter tables are in terms of a normalized lowpass prototype, the filter to be designed is usually reduced to a lowpass prototype. After the lowpass transfer function is

found, it is transformed to obtain the transfer function for the actual filter desired. Graph 1 shows the lowpass amplitude response which can be defined by four quantities.

Applications Information (Continued)
GRAPH I. Lowpass Prototype Response



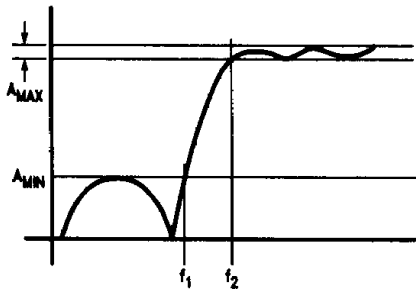
TL/K/10111-33

A_{MAX} = the maximum peak to peak ripple in the passband.
 A_{MIN} = the minimum attenuation in the stopband.
 f_C = the passband cutoff frequency.
 f_S = the stopband start frequency.

By defining these four quantities for the lowpass prototype the normalized pole and zero locations and the Q (quality) of the poles can be determined from tables or by computer programs.

To obtain the lowpass prototype for the highpass filter (Graph J) A_{MAX} and A_{MIN} are the same as for the lowpass case but $f_C = 1/f_2$ and $f_S = 1/f_1$.

GRAPH J. Highpass Response



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To obtain the lowpass prototype for a bandpass filter (Graph K) A_{MAX} and A_{MIN} are the same as for the lowpass case but

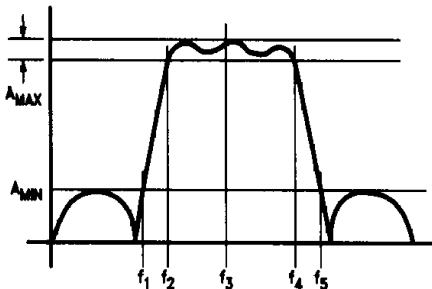
$$f_C = 1 \quad f_S = \frac{f_5 - f_1}{f_4 - f_2}$$

where $f_3 = \sqrt{f_1 f_5} = \sqrt{f_2 f_4}$ i.e., geometric symmetry

$$f_5 - f_1 = A_{MIN} \text{ bandwidth}$$

$$f_4 - f_2 = \text{Ripple bandwidth}$$

GRAPH K. Bandpass Response



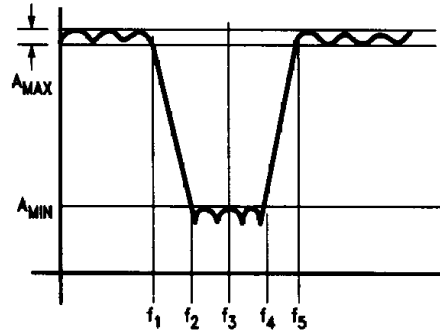
TL/K/10111-35

To obtain the lowpass prototype for the notch filter (Graph L) A_{MAX} and A_{MIN} are the same as for the lowpass case and

$$f_C = 1 \quad f_S = \frac{f_5 - f_1}{f_4 - f_2}$$

where $f_3 = \sqrt{f_1 f_5} = \sqrt{f_2 f_4}$

GRAPH L. Notch Response



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Normalized Lowpass Transformed to Un-Normalized Lowpass

The normalized lowpass filter has the passband edge normalized to unity. The un-normalized lowpass filter instead has the passband edge at f_C . The normalized and un-normalized lowpass filters are related by the transformation $s = s\omega_C$. This transforms the normalized passband edge $s = j$ to the un-normalized passband edge $s = j\omega_C$.

Normalized Lowpass Transformed to Un-Normalized Highpass

The transformation that can be used for lowpass to highpass is $S = \omega_C/s$. Since S is inversely proportional to s , the low frequency and high frequency responses are interchanged. The normalized lowpass $1/(S^2 + S/Q + 1)$ transforms to the un-normalized highpass

$$\frac{s^2}{s^2 + \frac{\omega_C}{Q}s + \omega_C^2}$$

Normalized Lowpass Transformed to Un-Normalized Bandpass

The transformation that can be used for lowpass to bandpass is $S = (s^2 + \omega_0^2)/BW$ where ω_0^2 is the center frequency of the desired bandpass filter and BW is the ripple bandwidth.

Normalized Lowpass Transformed to Un-Normalized Bandstop (or Notch)

The bandstop filter has a reciprocal response to a bandpass filter. Therefore a bandstop filter can be obtained by first transforming the lowpass prototype to a highpass and then performing the bandpass transformation.

SELECTION OF TRANSFER FUNCTION

The selection of a function which approximates the shape of the response desired is a complicated process. Except in the simplest cases it requires the use of tables or computer programs. The form of the transfer function desired is in terms of the pole and zero locations. The most common approximations found in tables are Butterworth, Tschebyscheff, Elliptic, and Bessel. The decision as to which approximation to use is usually a function of the requirements and

Applications Information (Continued)

system objectives. Butterworth filters are the simplest but have the disadvantage of requiring high order transfer functions to obtain sharp roll-offs.

The Tschebycheff function is a min/max approximation in the passband. This approximation has the property that it is equiripple which means that the error oscillates between maximums and minimums of equal amplitude in the passband. the Tschebycheff approximation, because of its equiripple nature, has a much steeper transition region than the Butterworth approximation.

The elliptic filter, also known as Caer or Zolotarev filters, are equiripple in the passband and stopband and have a steeper transition region than the Butterworth or the Tschebycheff.

For a specific lowpass filter three quantities can be used to determine the degree of the transfer function: the maximum passband ripple, the minimum stopband attenuation, and the transition ratio ($tr = \omega_S/\omega_C$). Decreasing A_{MAX} , increasing A_{MIN} , or decreasing tr will increase the degree of the transfer function. But for the same requirements the elliptic filter will require the lowest order transfer function. Tables and graphs are available in reference books such as "Reference Data for Radio Engineers", Howard W. Sams & Co., Inc., 5th Edition, 1970 and Erich Christian and Egon Eisenmann, "Filter Design Tables and Graphs", John Wiley and Sons, 1966.

For specific transfer functions and their pole locations such text as Louis Weinberg, "Network Analysis and Synthesis", McGraw Hill Book Company, 1962 and Richard W. Daniels, "Approximation Methods for Electronic Filter Design", McGraw-Hill Book Company, 1974, are available.

DESIGN OF CASCADED MULTISECTION FILTERS

The first step in designing is to define the response required and define the performance specifications:

1. Type of filter:
Lowpass, highpass, bandpass, notch, allpass
2. Attenuation and frequency response
3. Performance
Center frequency/corner frequency plus tolerance and stability
Insertion loss/gain plus tolerance and stability
Source impedance
Load impedance

- Maximum output noise
- Power consumption
- Power supply voltage
- Dynamic range
- Maximum output level

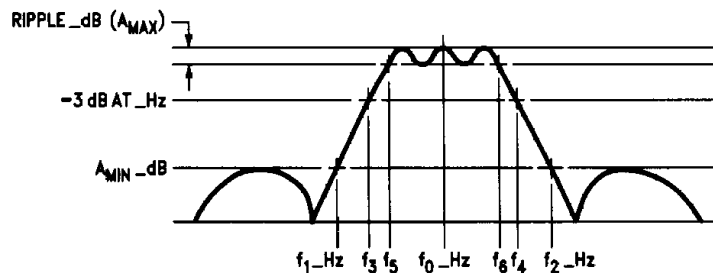
The second step is to find the pole and zero location for the transfer function which meet the above requirements. This can be done by using tables and graphs or network synthesis. The form of the transfer function which is easiest to convert to a cascaded filter is a product of first and second order terms in these forms:

| | | |
|---------------------------|---|------------|
| $\frac{K}{s + \omega_R}$ | $\frac{K}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$ | (lowpass) |
| $\frac{Ks}{s + \omega_R}$ | $\frac{Ks^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$ | (highpass) |
| | $\frac{Ks}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$ | (bandpass) |
| | $\frac{K(s^2 + \omega_z^2)}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$ | (notch) |
| | $\frac{s^2 - \frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$ | (allpass) |

Each of the second order functions is realizable by tuning an AF100 stage. By cascading these stages the desired transfer function is realized.

CASCADING SECOND ORDER STAGES

The primary concern in cascading second order stages is to minimize the maximum difference in amplitude from input to output over the frequencies of interest. A computer program is probably required in very complicated cases but some general rules that can be used that will usually give satisfactory results are:

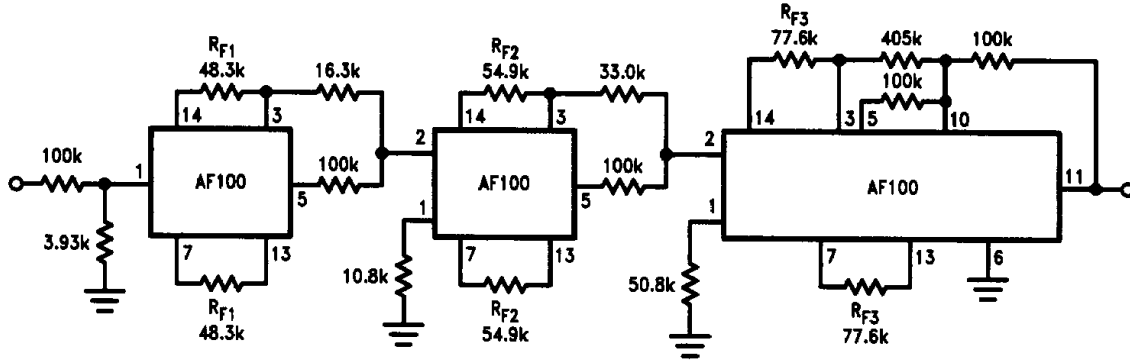


GRAPH M. Generalized Model Response

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Applications Information (Continued)

1. The highest "Q" pole pair should be paired with the zero pair closest in frequency.
2. If highpass and lowpass stages are cascaded the low-pass sections should be the higher frequency and high-pass sections the lower frequency.
3. In cascaded filters of more than two sections the first section should be the section with "Q" closest to 0.707 and then additional stages should be added in order of least difference between first stage Q and their Q.



TL/K/10111-38

Lowpass Elliptic Filter

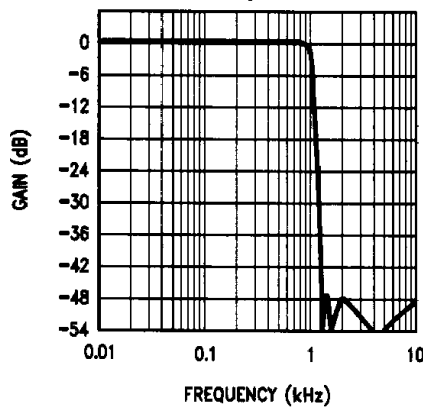
$F_C = 1$
 $F_S = 1.3$
 $A_{MAX} = 0.1 \text{ dB}$
 $A_{MIN} = 40 \text{ dB}$
 $N = 6$

$f_{O1} = 1.0415 \quad Q_1 = 7.88 \quad f_{Z1} = 1.329 \quad f_z/f_o = 1.28 \left(\frac{f_z}{f_o}\right)^2 = 1.63$
 $f_{O2} = 0.9165 \quad Q_2 = 1.79 \quad f_{Z2} = 1.664 \quad f_z/f_o = 1.82 \left(\frac{f_z}{f_o}\right)^2 = 3.30$
 $f_{O3} = 0.649 \quad Q_3 = 0.625 \quad f_{Z3} = 4.1285 \quad f_z/f_o = 6.36 \left(\frac{f_z}{f_o}\right)^2 = 40.5$

$R_{F1} = \frac{(503.3)}{f_{O1} \times f_C} \times 10^5 \quad R_{F2} = \frac{(503.3)}{f_{O2} \times f_C} \times 10^5 \quad R_{F3} = \frac{(503.3)}{f_{O3} \times f_C}$
 at 1000 Hz = f_C

$R_{F1} = 48.3k \quad R_{F2} = 54.9k \quad R_{F3} = 77.6k$

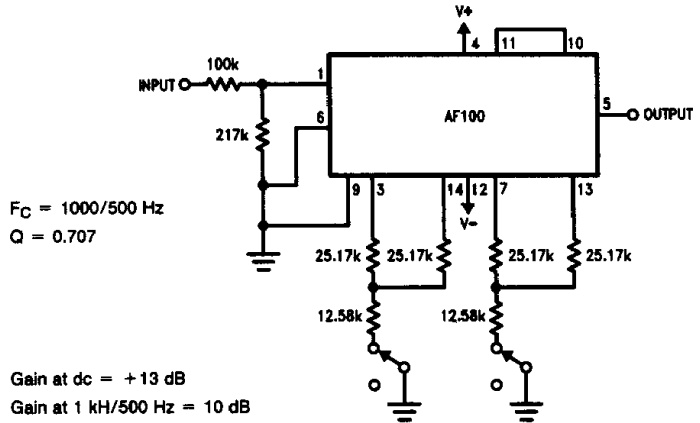
6th Order Elliptic Filter



TL/K/10111-39

FIGURE 21. Lowpass Elliptic Filter Example

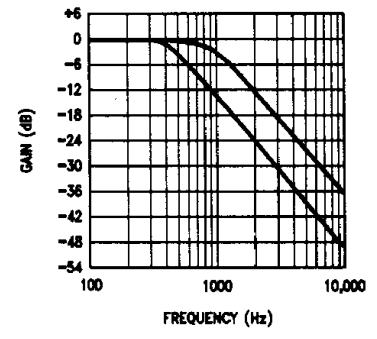
Applications Information (Continued)



$F_C = 1000/500 \text{ Hz}$
 $Q = 0.707$

Gain at dc = +13 dB
 Gain at 1 kHz/500 Hz = 10 dB

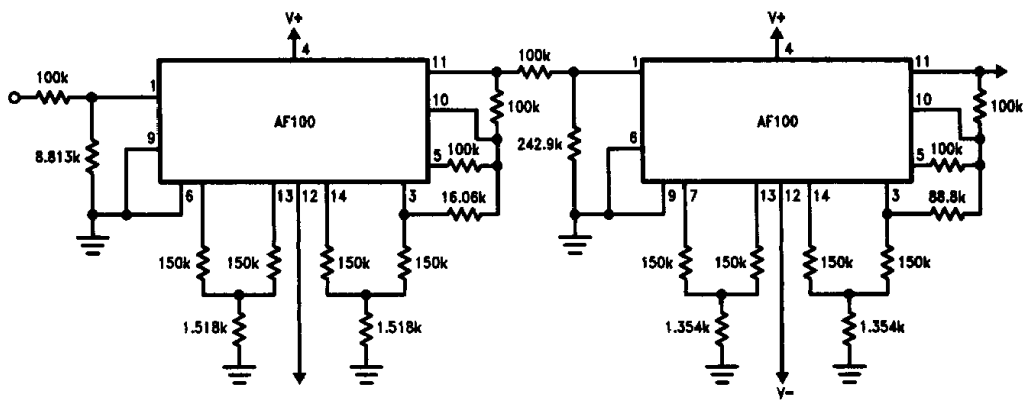
500/1000 Hz Switchable Butterworth Lowpass Filter



TL/K/10111-41

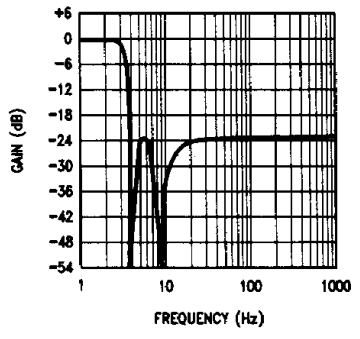
TL/K/10111-40

FIGURE 22. Switchable Filter Example: 500 Hz/1000 Hz Butterworth Lowpass



TL/K/10111-42

STAGE 1
 $F_C = 3.328 \text{ Hz}$
 $Q = 3.84$
 $F_Z = 4.218 \text{ Hz}$

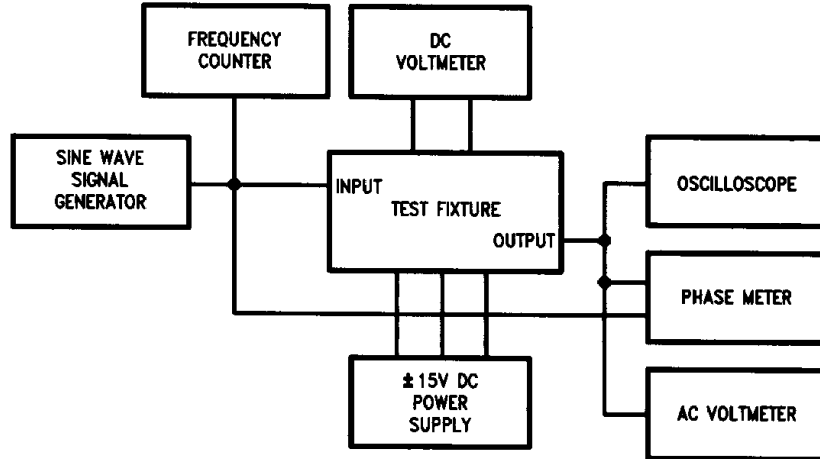


STAGE 2
 $F_C = 2.975 \text{ Hz}$
 $Q = 0.693$
 $F_Z = 8.865 \text{ Hz}$

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FIGURE 23. EEG Delta Filter—3 Hz Lowpass

Applications Information (Continued)



TL/K/10111-44

Input Level 1V rms 0 dBV

FIGURE 25. Test Circuit Block Diagram

COMPUTER AIDED DESIGN EXAMPLE*

This design is an example of a 60 Hz notch filter. The response is to have the following specifications:

Maximum passband ripple 0.1 dB

Minimum rejection 35 dB

0.1 dB bandwidth 15 Hz max

-35 dB bandwidth 1.5 Hz min

The steps in the design of this filter are:

1. Design a lowpass "prototype" for the filter.
2. Transformation of the lowpass prototype into a notch filter design.
3. Using the pole and zero locations found in step two calculate the value of the resistors required to build the filter.
4. Draw a schematic of filter using values obtained in step three.

*Computer programs shown are user interactive. Bold copy is user input, light copy is computer response, and line indications in parenthesis are included for easy identification of data common to several programs.

PROGRAM NO. 1

RUN

THIS PROGRAM DESIGNS BUTTERWORTH CHEBYCHEFF OR ELLIPTIC NORMALIZED LOWPASS FILTERS

WHAT TYPE OF FILTER? B-C-E

ELLIPTIC

DO YOU KNOW THE ORDER OF THE FILTER? Y/N

? **NO**

INPUT FC,FS,AMAX,AMIN

? **1, 10, .1, 35**

FC 1.000

FS 10.000

AMAX .100

AMIN 35.000

N 2.000

ATT AT FS -35.671 (ATTENUATION IN dB)

IS THIS SATISFACTORY? Y/N

? **YES**

F 1.823 (Line 1.1)

.775 (Line 1.2)

Z 14.124 (Line 1.3)

Applications Information (Continued)

PROGRAM NO. 2
(DETERMINES UN-NORMALIZED POLE + ZERO
LOCATIONS OF FIRST SECTION)
(DATA ENTERED FROM PROGRAM NO. 1)

RUN
 WHAT TYPE FILTER BANDPASS OR NOTCH
 ? **NOTCH**
 ENTER # OF POLE PAIRS? **1**
 ENTER # OF JW AXIS ZEROS? **1**
 ENTER # OF REAL POLES? **0**
 ENTER # OF ZEROS AT ZERO? **0**
 ENTER # OF COMPLEX ZEROS? **0**
 ENTER # OF REAL ZEROS? **0**
 ENTER F&Q OF EACH POLE PAIR
 ? **1.823, .775 (FROM LINE 1.1 AND LINE 1.2)**
 ENTER VALUES OF JW AXIS ZEROS
 ? **14.124 (FROM 1.3)**

ENTER FREQUENCY SCALING FACTOR
 ? **1**
 ENTER THE # OF FILTERS TO BE DESIGNED
 ? **1**
 ENTER THE C.F. AND BW OF EACH FILTER
 ? **60, 15**

OUTPUT OF PROGRAM NO. 2
TRANSFORMED POLE/ZERO LOCATIONS
FIRST SECTION

POLE LOCATIONS
 CENTER FREQ. Q
 56.93601 (From Line 2.3) 11.31813 (From Line 2.4)
 63.228877 (From Line 2.5) 11.31813 (From Line 2.6)
 JW AXIS ZEROS
 59.471339 (From Line 2.1)
 60.533361 (From Line 2.2)

PROGRAM NO. 3
(CHECK OF FILTER RESPONSE USING
PROGRAM NO. 2 DATA BASE)

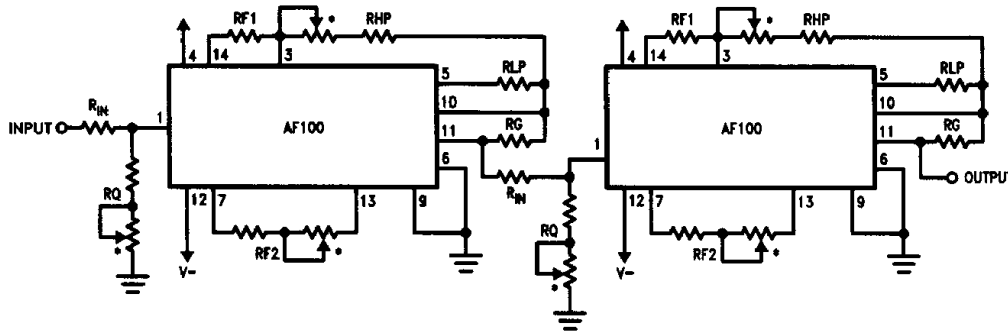
RUN
 NUMERATOR [ZEROS]
 $A(I)S^2 + R(I)S + Z(I)^2$
 1 0 59.471339 (From Line 2.1)
 1 0 60.533361 (From Line 2.2)
 REAL POLE
 COMPLEX POLE PAIRS
 F Q
 1 56.93601 11.31813 (From Lines 2.3 and 2.4)
 2 63.228877 11.31813 (From Lines 2.5 and 2.6)

RUN

| FREQ. | NOR. GAIN (DB) | PHASE | DELAY | NOR. DELAY | FREQ. | NOR. GAIN (DB) | PHASE | DELAY | NOR. DELAY |
|--------|----------------|--------|---------|------------|--------|----------------|--------|---------|------------|
| 40.000 | .032 | 347.69 | .002275 | 5.847169 | 60.600 | -47.102 | 169.17 | .050801 | 108.232021 |
| 45.000 | .060 | 342.20 | .004107 | 8.749738 | 60.800 | -33.650 | 165.48 | .051677 | 110.096278 |
| 50.000 | .100 | 330.70 | .009983 | 21.268142 | 61.000 | -27.577 | 161.72 | .052809 | 112.508334 |
| 55.000 | -.795 | 290.54 | .046620 | 99.324027 | 61.200 | -23.418 | 157.87 | .054167 | 115.403169 |
| 56.000 | -2.298 | 270.61 | .063945 | 136.234562 | 61.400 | -20.198 | 153.92 | .055712 | 118.694436 |
| 57.000 | -5.813 | 245.51 | .072894 | 155.299278 | 61.600 | -17.554 | 149.85 | .057391 | 122.270086 |
| 58.000 | -12.748 | 220.19 | .065758 | 140.096912 | 61.800 | -15.308 | 145.65 | .059136 | 125.989157 |
| 58.200 | -14.740 | 215.54 | .063369 | 135.006390 | 62.000 | -13.362 | 141.33 | .060869 | 129.681062 |
| 58.400 | -17.032 | 211.06 | .060979 | 129.914831 | 63.000 | -6.557 | 118.23 | .065975 | 140.559984 |
| 58.600 | -19.722 | 206.76 | .058692 | 125.043324 | 64.000 | -2.936 | 95.30 | .059402 | 126.556312 |
| 58.800 | -22.983 | 202.61 | .056588 | 120.561087 | 65.000 | -1.215 | 76.38 | .045424 | 96.774832 |
| 59.000 | -27.172 | 198.60 | .054724 | 116.589928 | 66.000 | -.463 | 62.43 | .032614 | 69.484716 |
| 59.200 | -33.235 | 194.72 | .053139 | 113.212012 | 67.000 | -.138 | 52.44 | .023498 | 50.062947 |
| 59.400 | -46.300 | 190.94 | .051856 | 110.478482 | 70.000 | .091 | 35.43 | .010452 | 22.267368 |
| 59.600 | -42.909 | 7.24 | .050888 | 108.417405 | 75.000 | .085 | 23.44 | .004250 | 9.054574 |
| 59.800 | -36.897 | 3.60 | .050242 | 107.040235 | 80.000 | .060 | 17.80 | .002310 | 4.921727 |
| 60.00 | -35.567 | 360.00 | .049916 | 106.346516 | 85.000 | .043 | 14.50 | .001460 | 3.110493 |
| 60.200 | -36.887 | 356.41 | .049907 | 106.326777 | 90.000 | .032 | 12.31 | .001011 | 2.154297 |
| 60.400 | -42.757 | 352.81 | .050206 | 106.963750 | | | | | |



Applications Information (Continued)



*Tuning Resistors
 0.1 dB bandwidth 15 Hz
 -35 dB bandwidth 1.5 Hz

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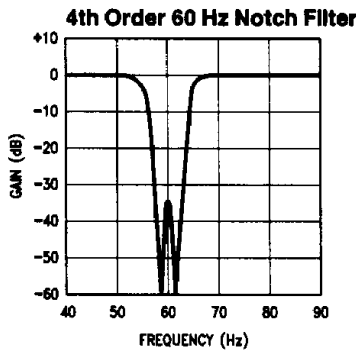
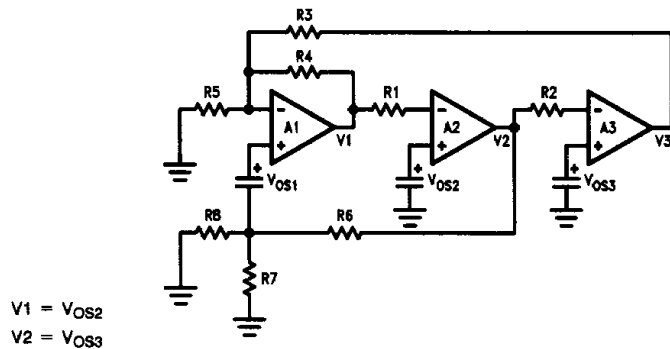


FIGURE 26. Implementations of a 60 Hz Notch from Computer Calculations

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V1 = V_{OS2}
 V2 = V_{OS3}

$$V_3 = \frac{\left[1 + \left(\frac{R_3 + R_5}{R_3 R_5} \right) R_4 \right] \left[V_{OS1} + V_{OS3} \left(\frac{R_7 R_8}{R_7 R_8 + R_6 (R_7 + R_8)} \right) \right] - V_{OS2}}{\frac{R_4}{R_3}}$$

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FIGURE 27. DC Output Voltage Due to Amplifier V_{OS}

DEFINITION OF TERMS

- A_{MAX} Maximum passband peak-to-peak ripple
- A_{MIN} Minimum stopband loss
- f_Z Frequency of jw axis pair
- f_O Frequency of complex pole pair
- Q Quality of pole
- f_C Passband edge
- f_S Stopband edge
- A_{HP} Gain from input to highpass output
- A_{BP} Gain from input to bandpass output
- A_{LP} Gain from input to lowpass output
- A_{AMP} Gain from input to output of amplifier
- R_f Pole frequency determining resistance
- R_Z Zero frequency determining resistance
- R_Q Pole quality determining resistance
- f_H Frequency above center frequency at which the gain decreases by 3 dB for a bandpass filter
- f_L Frequency below center frequency at which the gain decreases by 3 dB for a bandpass filter
- BW The bandwidth of a bandpass filter
- N Order of the denominator of a transfer function

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