design ideas

Edited by Brad Thompson

Bandpass filter features adjustable Q and constant maximum gain

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Applications such as audio equalizers require bandpass filters with a constant maximum gain that's independent of the filter's quality factor, Q. However, all of the well-known filter architectures—Sallen-Key, multiple-feedback, state-variable, and Tow-Thomas—suffer from altered maximum gain when Q varies. **Equation 1** expresses the second-order bandpass transfer function of a bandpass filter:

$$H_{BP}(s)=K\frac{\left(\frac{s}{\omega_0}\right)}{\left(\frac{s}{\omega_0}\right)^2+\frac{1}{Q}\left(\frac{s}{\omega_0}\right)+1}, \tag{1}$$

where K represents the filter's gain constant. When the input frequency equals ω_O, the filter's gain, A_{MAX}, is proportional to the product, KQ. Thus, modifying the quality factor alters the gain and vice versa.

This Design Idea describes a filter structure in which K is inversely proportional to Q. Altering Q also modifies K, producing a magnitude-plot set in which the curves maintain the same maximum gain at the central frequency ω_0—that is, KQ remains constant. **Figure 1** shows the filter, which comprises a twin T cell with an adjustable quality factor and a differential stage. The differential stage comprises op amp IC_3 and resistors R_{5A} through R_{5D}. This stage outputs the difference between the filter's input signal and the twin-T network's output. Capacitors C_1 and C_2 are of equal value, $C=C_1=C_2$, capacitor C_3 equals 2C, resistors R_1 and R_2 are also equal and of value $R=R_1=R_2$, and R_3 equals $R/_2$. **Equation 2** describes the twin-T circuit's transfer-function response as a notch filter producing output $V_{BR}(t)$:

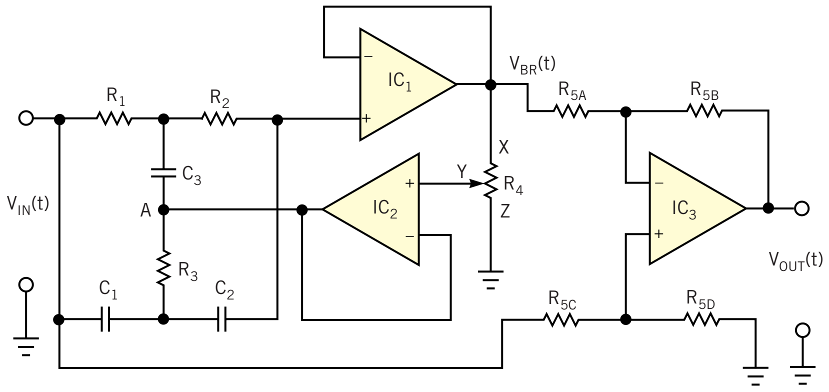

Figure 1 This bandpass active filter features adjustable Q and maximum gain in the passband and consists of a twin-T cell with Q adjustment and a differential output stage. You can also extract a frequency-notch output from the voltage-follower stage.

$$H_{BR}(s)=\frac{V_{BR}(s)}{V_{IN}(s)}=\frac{(RCs)^2+1}{(RCs)^2+4RC(1-m)s+1}. \tag{2}$$

Equation 3 describes the compete circuit's transfer function, a bandpass-filter response with output $V_{OUT}(t)$:

$$H_{BP}(s)=\frac{V_{OUT}(s)}{V_{IN}(s)}=\frac{4RC(1-m)s}{(RCs)^2+4RC(1-m)s+1}, \tag{3}$$

where m represents the twin-T cell's feedback factor. If you designate R_{XY} as the resistance potentiometer R_4's upper terminal, Point X; the rotor as Point Y; and R_{YZ} as the resistance between the rotor and the bottom terminal, Point Z, you can express m as the quotient of **Equation 4**:

$$m=\frac{R_{YZ}}{R_{XY}+R_{YZ}}=\frac{R_{YZ}}{R_4}. \tag{4}$$

Comparing **Equation 3** with the respective normalized transfer functions of a bandpass filter, **Equation 1**, **Equation 5** expresses the central frequency of the filter, ω_O, coincident with the transmission zero of the twin-T network:

$$\omega_0=\frac{1}{RC}. \tag{5}$$

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Equations 6 and **7**, respectively, give quality factor Q and gain constant K:

$$Q=\frac{1}{4(1-m)}; \tag{6}$$

$$K=\frac{1}{Q}=4(1-m). \tag{7}$$

The maximum gain, A_{MAX}, at $\omega=\omega_O$, always remains constant and equal to 1 (0 dB) and is independent of Q. The minimum quality factor is ¼ for m=0, which corresponds to the potentiometer's rotor connected to ground. The maximum gain is theoretically infinite, but, in practice, it's difficult to achieve a quality factor beyond 50. In most applications, Q ranges from 1 to 10.

Figure 2 shows the filter's magnitude and phase Bode plots for the frequency-notch output $V_{BR}(t)$ (available at IC_1's output) for values of m from 0.1 to 0.9. **Figure 3** shows Bode plots for the filter's bandpass output, $V_{OUT}(t)$, for the same values of m. In both graphs, frequency f_O equals 1061 Hz. To minimize frequency-response variations and improve response accuracy, you can build the filter with precision metal-film resistors of 1% or better tolerance. Likewise, use close-tolerance mica, polycarbonate, polyester, polystyrene, polypropylene, or Teflon capacitors. For best performance, avoid carbon resistors and electrolytic, tantalum, or ceramic capacitors.□

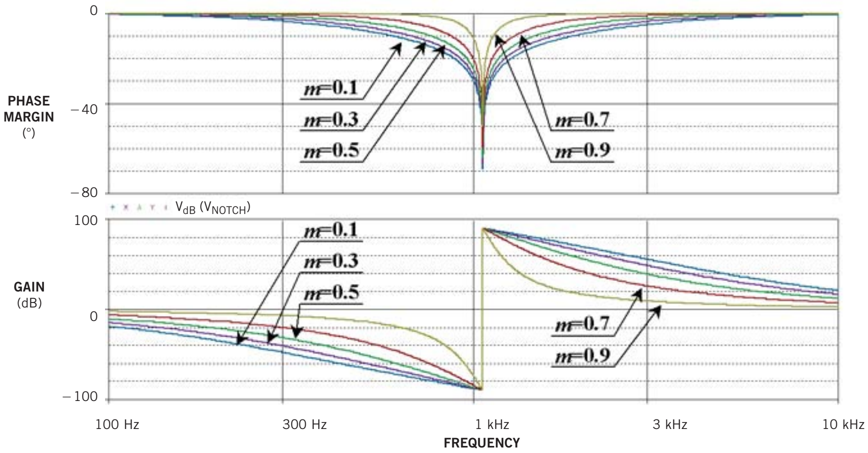

Figure 2 Magnitude and phase Bode plots at the frequency-notch output, $V_{BR}(t)$, show effects of varying twin-T-cell feedback factor, m, from 0.1 to 0.9.

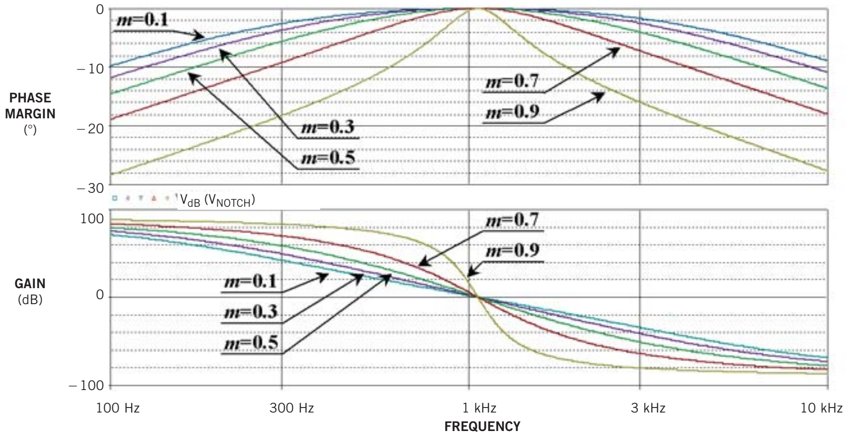

Figure 3 Magnitude and phase Bode plots at the bandpass output, $V_{OUT}(t)$, show effects of varying twin-T-cell feedback factor, m, from 0.1 to 0.9.