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:

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

**EQUATION 1**

where $K$ represents the filter's gain constant. When the input frequency equals $\omega_0$, 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 $\omega_0$ — 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 IC3 and resistors R3A through R3D. This stage outputs the difference between the filter’s input signal and the twin-T network’s output. Capacitors C1 and C2 are of equal value, $C=C_1=C_2$, capacitor $C_3$ equals 2C, resistors $R_1$ and $R_3$ are also equal and of value $R=R_1=R_3$, and $R_2$ equals $R/2$. **Equation 2** describes the twin-T circuit’s transfer-function response as a notch filter producing output $V_{BR}(t)$:

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

**EQUATION 2**

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

$$m = \frac{R_{YZ}}{R_{XY} + R_{YZ}} = \frac{R_{YZ}}{R_4}. \text{\hspace{1cm} EQUATION 4}$$

Comparing Equation 3 with the respective normalized transfer functions of a bandpass filter, Equation 1, Equation 5 expresses the central frequency of the filter, $\omega_0$, coincident with the transmission zero of the twin-T network:

$$\omega_0 = \frac{1}{RC}. \text{\hspace{1cm} EQUATION 5}$$

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

$$Q = \frac{1}{4(1-m)}. \text{\hspace{1cm} EQUATION 6}$$

$$K = \frac{1}{Q} = 4(1-m). \text{\hspace{1cm} EQUATION 7}$$

The maximum gain, $A_{MAX}$, at $\omega = \omega_0$, always remains constant and equal to 1 (0 dB) and is independent of $Q$. The minimum quality factor is $1/4$ 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 IC1'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 $f_0$ 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.

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