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Sallen-Key Filters

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IN THIS MINI TUTORIAL

Three sample Sallen-Key filters are designed in this mini tutorial, one in a series of mini tutorials describing discrete circuits for precision op amps.

The Sallen-Key configuration, also known as a voltage control voltage source (VCVS), was first introduced in 1955 by R. P. Sallen and E. L. Key of MIT's Lincoln Labs (see the References section). One of the most widely used filter topologies, this configuration is shown in Figure 1.

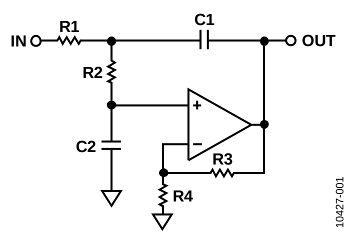

Figure 1. Sallen-Key Low-Pass Filter

One reason for this popularity is that this configuration shows the least dependence of filter performance on the performance of the op amp. This is because the op amp is configured as an amplifier, as opposed to an integrator, which minimizes the gain-bandwidth requirements of the op amp.

This infers that for a given op amp, one can design a higher frequency filter than with other topologies since the op amp gain-bandwidth product does not limit the performance of the filter as it would if it were configured as an integrator. In addition, since the op amp is configured as an amplifier, current feedback amplifiers, which cannot be configured as conventional integrators, can be used. This allows slightly more bandwidth from the filter. The signal phase through the filter is maintained (noninverting configuration).

Another advantage of this configuration is that the ratio of the largest resistor value to the smallest resistor value, and the ratio of the largest capacitor value to the smallest capacitor value (component spread) are low, which is beneficial for manufacturability. The frequency and Q terms are somewhat independent, but they are very sensitive to the gain parameter. The Sallen-Key is very Q-sensitive to element values, especially for high Q sections. The design equations for the Sallen-Key low-pass filter are shown in the Sallen-Key Low-Pass Design Equations section.

While the Sallen-Key filter is widely used, a serious drawback is that the filter is not easily tuned, due to interaction of the component values on F_0 and Q. Another limitation is the relatively low maximum Q value obtainable.

To transform the low pass into the highpass, simply exchange the capacitors and the resistors in the frequency determining network (that is, not the amp gain resistors). This is shown in Figure 2. The comments regarding sensitivity of the filter given above for the low-pass case apply to the high-pass case as well. The design equations for the Sallen-Key high-pass filter are shown in the Sallen-Key High-Pass Design Equations section.

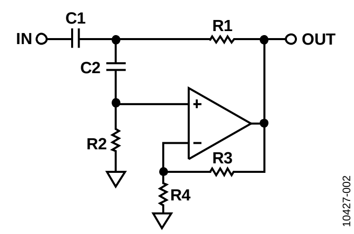

Figure 2. Sallen-Key High-Pass Filter

The band-pass case of the Sallen-Key filter (see Figure 4) has a severe limitation. The value of Q determines the gain of the filter, that is, it cannot be set independently, as it can with the low-pass or high-pass cases. The design equations for the Sallen-Key band-pass filter are shown in the Sallen-Key Band-Pass Design Equations section.

Although a Sallen-Key notch filter may also be constructed, notch filters have a large number of undesirable characteristics. The resonant frequency, or the notch frequency, cannot be adjusted easily due to component interaction.

As in the band-pass case, the section gain is fixed by the other design parameters, and there is a wide spread in component values, especially capacitors. Because of these issues and the availability of easier to use circuits, notch filters are not discussed in this tutorial.

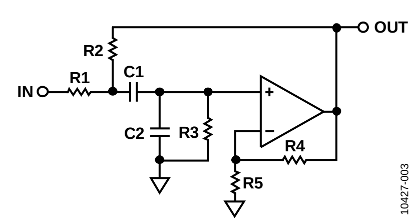

Figure 3. Sallen-Key Band-Pass Filter

SALLEN-KEY LOW-PASS DESIGN EQUATIONS

$$\frac{+H\ \omega_0 2}{s^2 + \alpha\ \omega_0 s + \omega_0{}^2}$$

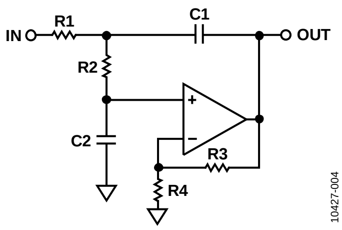

Figure 4.

$$\frac{V_O}{V_{IN}} = \frac{H \dfrac{1}{R1\ R2\, C1\, C2}}{s^2 + s\left[\left(\dfrac{1}{R1} + \dfrac{1}{R2}\right)\dfrac{1}{C1} + \dfrac{(1 - H)}{R2\, C2}\right] + \dfrac{1}{R1\, R2\, C1\, C2}}$$

To design the filter, choose C1 and R3.

Then

$$k = 2\ \pi\ F_0\ C1$$

$$R4 = \frac{R3}{(H - 1)}$$

$$m = \frac{\alpha 2}{4} + (H - 1)$$

$$C2 = m\ C1$$

$$R1 = \frac{2}{\alpha\ k}$$

$$R2 = \frac{\alpha}{2\ mk}$$

SALLEN-KEY HIGH-PASS DESIGN EQUATIONS

$$\frac{+H\ s^2}{s^2 + \alpha\ \omega_0 s + \omega_0{}^2}$$

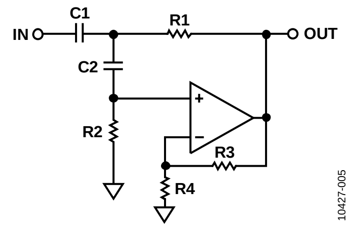

Figure 5.

$$\frac{V_O}{V_{IN}} = \frac{H\ s^2}{s^2 + s\left[\dfrac{\dfrac{C2}{R2} + \dfrac{C1}{R2} + (1 - H)\dfrac{C2}{R1}}{C1\, C2}\right] + \dfrac{1}{R1\, R2\, C1\, C2}}$$

To design the filter, choose C1 and R3.

Then

$$k = 2\ \pi\ F_0\ C1$$

$$C2 = C1$$

$$R1 = \frac{\alpha + \sqrt{\alpha^2 + (H - 1)}}{4\, k}$$

$$R2 = \frac{4}{\alpha + \sqrt{\alpha^2 + (H - 1)}} + \frac{1}{k}$$

SALLEN-KEY BAND-PASS DESIGN EQUATIONS

$$\frac{+H\ \omega_0 s}{s^2 + \alpha\ \omega_0 s + \omega_0^{\ 2}}$$

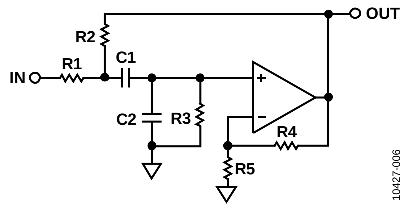

Figure 6.

$$\frac{V_O}{V_{IN}} =$$

$$\frac{H\ s\dfrac{1}{R1\,C2}}{s^2\ + s\left[\dfrac{\dfrac{C1}{R3}+\dfrac{(C1+C2)}{R1}+\dfrac{C2}{R2}+\dfrac{C1}{R2}(1-H)}{C1\ C2}\right]+\dfrac{1}{R3+C1\,C2}\left(\dfrac{R1+R2}{R1\,R2}\right)}$$

To design the filter, choose C1 and R4.

Then

$$k = 2\ \pi\ F_0\ C1$$

$$R5 = \frac{R4}{H-1}$$

$$C2 = \frac{1}{2}C1$$

$$R1 = \frac{2}{k}$$

$$R2 = \frac{2}{3\,k}$$

$$R3 = \frac{4}{k}$$

$$H = \frac{1}{3}\left(6.5 - \frac{1}{Q}\right)$$

REFERENCES

Sallen, R. P. and E. L. Key, 1955. "A Practical Method of Designing RC Active Filters." *IRE Transactions on Circuit Theory*, Vol. CT-2, 74–85.

Zumbahlen, Hank, editor, 2008. *Linear Circuit Design Handbook*, Newnes, ISBN 978-0-7506-8703-4.

REVISION HISTORY

7/12—Rev. 0 to Rev. A

Changes to Statements following Equations..................................2

3/12—Revision 0: Initial Version

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