Switched-Capacitor Filters

The characteristics of all active filters, regardless of architecture, depend on the accuracy of their RC time constants. Because the typical precision achieved for integrated resistors and capacitors is approximately ±30%, a designer is handicapped when attempting to use absolute values for the components in an integrated filter circuit. The ratio of capacitor values on a chip can be accurately controlled, however, to about one part in 2000. Switched-capacitor filters use these capacitor ratios to achieve precision without the need for precise external components.

In the switched-capacitor integrator shown in **Figure 12**, the combination of C_1 and the switch simulates a resistor.

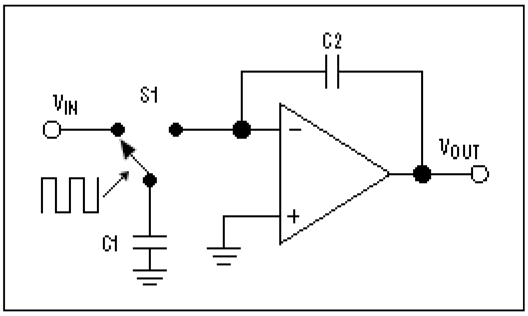

Figure 12. A switched-capacitor integrator

The switch S_1 toggles continuously at a clock frequency f_{CLK}. Capacitor C_1 charges to V_{IN} when S_1 is to the left. When it switches to the right, C_1 dumps charge into the integrator's summing node, from which it flows into the capacitor C_2. The charge on C_1 during each clock cycle is

$Q = C_1 V_{IN}$,

and thus the average current transferred to the summing junction is

$I = Qf_C = C_1V_{IN}\times f_C$

Notice that the current is proportional to V_{IN}, so we have the same effect as a resistor of value

$R = V_{IN}/I = 1/ C_1f_C$

The integrator's ω_0 is therefore

$\omega_0 = 1/RC_2 = C_1f_C/C_2$

Because ω_0 is proportional to the ratio of the two capacitors, its value can be controlled with great accuracy. Moreover, the value is proportional to the clock frequency, so you can vary the filter characteristics by changing f_{CLK}, if desired. But the switched capacitor is a sampled-data system and therefore not completely equivalent to the time-continuous RC integrator. The differences, in fact, pose three issues for a designer.

Which Approach is Best? Active, Passive, or Switched-Capacitor?

Each filter technology offers a unique set of advantages and disadvantages that makes it a nearly ideal solution to some filtering problems and completely unacceptable in other applications. Here's a quick look at the most important differences between active, passive, and switched-capacitor filters.

Accuracy: Switched-capacitor filters have the advantage of better accuracy in most cases. Typical center-frequency accuracies are normally on the order of about 0.2% for most switched-capacitor ICs, and worst-case numbers range from 0.4% to 1.5% (assuming, of course, that an accurate clock is provided). In order to achieve this kind of precision using passive or conventional active filter techniques requires the use of either very accurate resistors, capacitors, and sometimes inductors, or trimming of component values to reduce errors. It is possible for active or passive filter designs to achieve better accuracy than switched-capacitor circuits, but additional cost is the penalty. A resistor-programmed switched-capacitor filter circuit can be trimmed to achieve better accuracy when necessary, but again, there is a cost penalty.

Cost: No single technology is a clear winner here. If a single-pole filter is all that is needed, a passive RC network may be an ideal solution. For more complex designs, switched-capacitor filters can be very inexpensive to buy, and take up very little expensive circuit board space. When good accuracy is necessary, the passive components, especially the capacitors, used in the discrete approaches can be quite expensive; this is even more apparent in very compact designs that require surface-mount components. On the other hand, when speed and accuracy are not important concerns, some conventional active filters can be built quite cheaply.

Noise: Passive filters generate very little noise (just the thermal noise of the resistors), and conventional active filters generally have lower noise than switched-capacitor ICs. Switched-capacitor filters use active op amp-based integrators as their basic internal building blocks. The integrating capacitors used in these circuits must be very small in size, so their values must also be very small. The input resistors on these integrators must therefore be large in value in order to achieve useful time constants. Large resistors produce high levels of thermal noise voltage; typical output noise levels from switched-capacitor filters are on the order of 100 µV to 300 µVrms over a 20 kHz bandwidth. It is interesting to note that the integrator input resistors in switched-capacitor filters are made up of switches and capacitors, but they produce thermal noise the same as "real" resistors.

(Some published comparisons of switched-capacitor vs. op amp filter noise levels have used very noisy op amps in the op amp-based designs to show that the switched-capacitor filter noise levels are nearly as good as those of the op amp-based filters. However, filters with noise levels at least 20 dB below those of most switched-capacitor designs can be built using low-cost, low-noise op amps such as the LM833.)

Although switched-capacitor filters tend to have higher noise levels than conventional active filters, they still achieve dynamic ranges on the order of 80 dB to 90 dB—easily quiet enough for most applications, provided that the signal levels applied to the filter are large enough to keep the signals "out of the mud".

Thermal noise isn't the only unwanted quantity that switched-capacitor filters inject into the signal path. Since these are clocked devices, a portion of the clock waveform (on the order of 10 mV p–p) will make its way to the filter's output. In many cases, the clock frequency is high enough compared to the signal frequency that the clock feedthrough can be ignored, or at least filtered with a passive RC network at the output, but there are also applications that cannot tolerate this level of clock noise.

Offset Voltage: Passive filters have no inherent offset voltage. When a filter is built from op amps, resistors and capacitors, its offset voltage will be a simple function of the offset voltages of the op amps and the dc gains of the various filter stages. It's therefore not too difficult to build filters with sub-millivolt offsets using conventional techniques. Switched-capacitor filters have far larger offsets, usually ranging from a few millivolts to about 100 mV; there are some filters available with offsets over 1V! Obviously, switched-capacitor filters are inappropriate for applications requiring dc precision unless external circuitry is used to correct their offsets.

Frequency Range: A single switched-capacitor filter can cover a center frequency range from 0.1 Hz or less to 100 kHz or more. A passive circuit or an op amp/resistor/capacitor circuit can be designed to operate at very low frequencies, but it will require some very large, and probably expensive, reactive components. A fast operational amplifier is necessary if a conventional active filter is to work properly at 100 kHz or higher frequencies.

Tunability: Although a conventional active or passive filter can be designed to have virtually any center frequency that a switched-capacitor filter can have, it is very difficult to vary that center frequency without changing the values of several components. A switched-capacitor filter's center (or cutoff) frequency is proportional to a clock frequency and can therefore be easily varied over a range of 5 to 6 decades with no change in external circuitry. This can be an important advantage in applications that require multiple center frequencies.

Component Count/Circuit Board Area: The switched-capacitor approach wins easily in this category. The dedicated, single-function monolithic filters use no external components other than a clock, even for multipole transfer functions, while passive filters need a capacitor or inductor per pole, and conventional active approaches normally require at least one op amp, two resistors, and two capacitors per second-order filter. Resistor-programmable switched-capacitor devices generally need four resistors per second-order filter, but these usually take up less space than the components needed for the alternative approaches.

Aliasing: Switched-capacitor filters are sampled-data devices, and will therefore be susceptible to aliasing when the input signal contains frequencies higher than one-half the clock frequency. Whether this makes a difference in a particular application depends on the application itself. Most switched-capacitor filters have clock-to-center-frequency ratios of 50:1 or 100:1, so the frequencies at which aliasing begins to occur are 25 or 50 times the center frequencies. When there are no signals with appreciable amplitudes at frequencies higher than one-half the clock frequency, aliasing will not be a problem. In a low-pass or bandpass application, the presence of signals at frequencies nearly as high as the clock rate will often be acceptable because although these signals are aliased, they are reflected into the filter's stopband and are therefore attenuated by the filter.

When aliasing is a problem, it can sometimes be fixed by adding a simple, passive RC low-pass filter ahead of the switched-capacitor filter to remove some of the unwanted high-frequency signals. This is generally effective when the switched-capacitor filter is performing a low-pass or bandpass function, but it may not be practical with high-pass or notch filters because the passive anti-aliasing filter will reduce the passband width of the overall filter response.

Design Effort: Depending on system requirements, either type of filter can have an advantage in this category, but switched-capacitor filters are generally much easier to design. The easiest-to-use devices, such as the LMF40, require nothing more than a clock of the appropriate frequency. A very complex device like the LMF120 requires little more design effort than simply defining the desired performance characteristics. The more difficult design work is done by the manufacturer (with the aid of some specialized software). Even the universal, resistor-programmable filters like the LMF100 are relatively easy to design with. The procedure is made even more user-friendly by the availability of filter software from a number of vendors that will aid in the design of LMF100-type filters. National Semiconductor provides one such filter software package free of charge. The program allows the user to specify the filter's desired performance in terms of cutoff frequency, a passband ripple, stopband attenuation, etc., and then determines the required characteristics of the second-order sections that will be used to build the filter. It also computes the values of the external resistors and produces amplitude and phase vs. frequency data.

Where does it make sense to use a switched-capacitor filter and where would you be better off with a continuous filter? Let's look at a few types of applications:

Tone Detection (Communications, FAXs, Modems, Biomedical Instrumentation, Acoustical Instrumentation, ATE, etc.): Switched-capacitor filters are almost always the best choice here by virtue of their accurate center frequencies and small board space requirements.

Noise Rejection (Line-Frequency Notches for Biomedical Instrumentation and ATE, Low-Pass Noise Filtering for General Instrumentation, Anti-Alias Filtering for Data Acquisition Systems, etc.): All of these applications can be handled well in most cases by either switched-capacitor or conventional active filters. Switched-capacitor filters can run into trouble if the signal bandwidths are high enough relative to the center or cutoff frequencies to cause aliasing, or if the system requires dc precision. Aliasing problems can often be fixed easily with an external resistor and capacitor, but if dc precision is needed, it is usually best to go to a conventional active filter built with precision op amps.

Controllable, Variable Frequency Filtering (Spectrum Analysis, Multiple-Function Filters, Software-Controlled Signal Processors, etc.): Switched-capacitor filters excel in applications that require multiple center frequencies because their center frequencies are clock-controlled. Moreover, a single filter can cover a center frequency range of 5 decades. Adjusting the cutoff frequency of a continuous filter is much more difficult and requires either analog switches (suitable for a small number of center frequencies), voltage-controlled amplifiers (poor center frequency accuracy) or DACs (good accuracy over a very limited control range).

Audio Signal Processing (Tone Controls and Other Equalization, All-Pass Filtering, Active Crossover Networks, etc.): Switched-capacitor filters are usually too noisy for "high-fidelity" audio applications. With a typical dynamic range of about 80 dB to 90 dB, a switched-capacitor filter will usuallly give 60 dB to 70 dB signal-to-noise ratio (assuming 20 dB of headroom). Also, since audio filters usually need to handle three decades of signal frequencies at the same time, there is a possibility of aliasing problems. Continuous filters are a better choice for general audio use, although many communications systems have bandwidths and S/N ratios that are compatible with switched capacitor filters, and these systems can take advantage of the tunability and small size of monolithic filters.