A Simple Digitally Tunable Active RC Filter

by Philip Karantzalis

Introduction

The tuning of the cutoff frequency ($f_{CUTOFF}$) of an active RC filter can be implemented using switched-capacitor circuits or continuous time circuits. In applications that require infinite tuning resolution of an any-order filter in a single IC package, a switched-capacitor approach is preferable (simply changing the clock frequency tunes $f_{CUTOFF}$). In applications that require tuning a continuous time filter to just a few cutoff frequencies, tuning can be implemented using op amps, CMOS switches and resistor or capacitor arrays.

Continuous time filters can also be tuned with high resolution over a large frequency range via digital control by using DACs to multiply the RC time constant of op-amp-based integrators (for example, an 8-bit DAC-based tuner allows for 256 frequency steps). Figure 1 shows a simple, low order and low cost continuous time filter circuit.

It can be tuned to a few cutoff frequencies via a Serial Peripheral Interface (SPI). This is a simpler alternative to using switches with resistor or capacitor arrays or multiple DACs that require a large number of active and passive components.

Digital control through an SPI is useful in a variety of applications to control band-limiting for sensor and transducer signals. Typical applications are: accelerometers for vibration analysis, hydrophones for sonar detection, LVDTs for linear motion measurements and microphones for sound reception and recording.

An SPI-Tunable Second Order Filter

The Figure 1 circuit is a state-variable second order filter using two ICs, a low noise CMOS quad op amp (LTC6242) and a low noise dual Programable Gain Amplifier, PGA (LTC6912-X). The gains of the two LTC6912-X amplifiers (GA and GB) are independently programmed via SPI control. The SPI controlled gain settings of an LTC6912-1 are 1, 2, 5, 10, 20, 50 and 100 and for an LTC6912-2 1, 2, 4, 8, 16, 32 and 64. The Figure 1 filter has three inverting outputs providing a highpass, bandpass and lowpass frequency responses. An optional inverting amplifier connected to one of the three outputs provides for a noninverting or a differential filter output. The filter's second order transfer function is a function of the circuit's resonant frequency, $f_0$ and Q values.

The $f_0$ frequency is equal to the integrator's RC constant, the dual PGA gain and the ratio of resistors $R_4$ and $R_2$ (if $R_4 = R_2$ and $G_A = G_B = Gain$ then $f_0 = Gain/2\pi RC$). The filter's Q value is equal the ratio of resistors $R_3$ and $R_2$ and the two PGA gains (if $R_4 = R_2$ and $G_A = G_B$ then $Q = R_3/R_2$).

The filter's passband gain is equal to the ratio of $R_4/R_1$, $R_3/R_1$ and $R_2/R_1$.

**Figure 1.** An SPI tunable second order active RC filter.
for a lowpass, bandpass and highpass filters respectively.

**A Tunable Lowpass or Highpass Filter**

The shape of the amplitude response of the second order depends on the $f_0$ frequency relative to the cutoff frequency and the Q value. In a second order Butterworth highpass or lowpass response the $f_0$ frequency is equal to $f_{\text{CUTOFF}}$ (f–3dB) and the filter’s Q value is equal to 0.707. In a second order Bessel highpass or lowpass response the $f_0$ frequency is equal to $1.274 \cdot f_{\text{CUTOFF}}$ and the filter’s Q value is equal to 0.577. Figure 2 shows the tunable range of a Butterworth lowpass filter using an 100Hz integrator frequency ($R = 1.58M\Omega$, ±1% and $C = 1000pF$, ±5%) and an LTC6912-2 to tuned the filter’s $f_{\text{CUTOFF}}$ from 100Hz to 6.4kHz.

Figure 3 shows the tunable range of a Butterworth highpass filter that is the mirror opposite of the lowpass filter response of Figure 2. The output response to a step change is approximately equal to $5/f_{\text{CUTOFF}}$, (if the step change is to a 1kHz $f_{\text{CUTOFF}}$ then the filter settles five milli-seconds after a step change). The maximum tunable $f_0$ frequency is a function of the gain-bandwidth product of the op amps and the circuit’s sensitivity to the highest PGA gain that is used for tuning. For the amplifiers shown, based on empirical data, a maximum $f_0$ of $800kHz/[Q \cdot \text{Gain}]$ limits gain error to $\leq 2\text{dB})$. For example, if only the lowest 1, 2, 5 and 10 gains of an LTC6912-1 are used for tuning, a second order Butterworth lowpass filter ($f_0 = f_{\text{CUTOFF}}$)
P-channel MOSFET switch is turned on continuously, thereby maximizing the usable battery life.

A Power-On Reset output is available for microprocessor systems to insure proper startups. Internal overvoltage and undervoltage comparators on both outputs will pull the POR output low if the output voltages are not within ±8.5%. The POR output is delayed by 262,144 clock cycles (about 175ms) after achieving regulation, but will be pulled low immediately when either output is out of regulation.

**A High Efficiency 2.5V and 1.8V Step-Down DC/DC Regulator with all Ceramic Capacitors**

The low cost and low ESR of ceramic capacitors make them a very attractive choice for use in switching regulators. In addition, ceramic capacitors have a benign failure mechanism unlike tantalum capacitors. Unfortunately, the ESR is so low that it can cause loop stability issues. A solid tantalum capacitor’s ESR generates a loop zero at 5kHz–50kHz that can be instrumental in giving acceptable loop phase margin. Ceramic capacitors, on the other hand, remain capacitive to beyond 300kHz and usually resonate with their ESL before the ESR becomes effective. Also, inexpensive ceramic capacitors are prone to temperature and voltage effects, requiring the designer to check loop stability over the operating temperature range. For these reasons, great care is usually needed when using only ceramic input and output capacitors. The LTC3548 was designed with ceramic capacitors in mind and is internally compensated to handle these difficult design considerations. High quality X5R or X7R ceramic capacitors should be used to minimize the temperature and voltage coefficients.

Figure 4 shows the bandpass filter of Figure 1 tuned from 2kHz to 16kHz using a 2kHz integrator frequency (R = 205k, ±1% and C = 390pF, ±5%) and an LTC6912-2 with gain settings 1, 2, 4 and 8 the notch frequency is tuned to 500Hz, 1kHz, 2kHz and 4kHz respectively. Any of the filters discussed above can be made into SPI-tunable fourth order filters by cascading two second order circuits.

**Notes**

1 SPI is a synchronous communication protocol using a 3-wire interface between a microprocessor and a peripheral device.