USE OF SWITCHED CAPACITOR FILTERS IN FREQUENCY PROGRAMMABLE APPLICATIONS

by

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Abstract

A requirement that often arises in Communication Engineering Laboratory and research applications, is to change the bandwidth characteristics of the frequency selective blocks of a given system in a predetermined manner. The method that has been traditionally employed is to vary the values of the components themselves so that the transfer function will be altered to match the required bandwidth characteristics.

This approach has several limitations. The most notable one is the non-linear relationship between the component values and the cut-off frequencies. When variable resistors and capacitors are used, this non-linearity seriously affects the ergonomy of the user interface. Even if digitally controlled devices are used, at least an intermediate firmware block will still be necessary to present a linear transfer function to the front end.

A group of devices now becoming increasingly popular, called switched capacitor filters, in which the cut-off frequency is directly controlled through an external clock, provides a convenient alternative to the above problem. By controlling the frequency of the external clock precisely and as required, very effective and versatile control of the bandwidth characteristics may be achieved.

This paper examines the problems associated with the traditional approach and explains how the use of switched capacitor filters eliminates them. It also deals with the operating principle of switched capacitor filters and concludes with a case study of a frequency programmable application designed by the authors using a switched capacitor low pass filter.

1.0 Introduction

Almost all electronic systems include frequency selective blocks called filters. A filter is a two port device ideally having a window function in the frequency domain. Their purpose is to emphasize signals in certain frequency ranges and reject signals in other ranges.

What determines the characteristics of a filter are the values of the components comprising it. These include resistors as well as reactive components i.e. capacitors and inductors. Inductors are now rarely used and are generally replaced by active equivalents. In either case the so-called cut-off frequencies of a filter are rational functions of the component values.

Consequently, when it is required to alter the cut-off frequency of a filter block, it is necessary to alter these component values themselves. This can be achieved with the use of variable components. Variable resistors are available in a wide range of values in both linear and logarithmic form. Tunable capacitors are also widely available. The values of these components are mechanically alterable using spindles or slides. Such components are ideal for applications where the user is required to make alterations to the frequency characteristics.

When rapid and precise alteration of component values is required, it is more suitable to employ electronic control as opposed to mechanical control outlined above.

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Semiconductor devices provide variable resistance and capacitance but over a smaller range, over a wide range, but capacitance over a smaller range. Field Effect Transistors (FETs) are a convenient and relatively cheap means of obtaining electronically variable resistors while varactor diodes are ideal as electronically tunable capacitors. Electronic tuning is also more suitable when feedback control needs to be employed.

Both electronic and mechanical control of components described above are basically analog control where the value of the component becomes a linear function of some physical parameter like the angular displacement of a spindle, linear displacement of a slide, a voltage or a current. However, a recent trend has been the increased use of digital control where the user or a circuit provides the control parameter in the form of a binary number. Digitally controlled potentiometers are now available and can be used to replace the resistors in a filter circuit and the values may be digitally controlled. This type of control is more suited for frequency programmable applications where the inputs that are required to control the frequency are generally in digital form. Tradition demands that the word programmability should imply some form of digital control as opposed to conventional analog control like tuning spindles although the end result is the same.

The Control of the cut-off frequencies through the alteration of component values has serious limitations as will be seen later. Much research had been inspired in the search of alternative means of controlling the cut-off characteristics of filters. The switched capacitor filters have been an important breakthrough.

2.0 Drawbacks of the Method of Altering Component Values

The drawbacks in the method of controlling the cut-off frequency of a filter by manipulating component values stem from a single source, "the lack of linearity".

In almost all filters, the cut-off frequencies are reciprocals of the system time constants. As a result the cut-off frequency varies with the component value in a hyperbolic manner. For example, for the simplest of all low pass filters shown in FIGURE 1, the cut-off frequency is given by:

\[ f_c = \frac{1}{2\pi CR} \]  

Figure 1. Simple Low Pass Filter

No appreciable variation of fo. This type of variation in a control is particularly unsuitable in applications where the control is in the front end to be manipulated directly by the user.

More complex filter circuits than the one shown in Figure 1 will have more complex transfer functions but the relationship between the cut-off frequencies and component values would still be of reciprocal nature. Therefore, the fundamental problem of non-linearity will remain irrespective of the circuit.

Another problem encountered with the use of continuously variable components is that because the variation is continuous, the resulting variation in the cut-off frequency is also continuous. It has to sweep through a range of values to reach the desired value. This may cause problems if a region of instability has to be passed on the way. For example, when a potentiometer is being varied to obtain the desired frequency characteristics, it may reach a value corresponding to a resonant condition which may momentarily give an undesired output as the pot sweeps past that value. This could be avoided by having two or more potentiometers with ranges not encompassing the resonant value and having some means of selecting from among them. Use of digitally controlled components is another effective way of getting around this problem. A digitally controlled potentiometer can achieve a step change in its value depending on the binary input. Step changes in the component values will result in a step change in the cut-off frequency without the circuit having to progressively sweep through the frequency axis and as a result, unstable regions could be avoided by proper design.
The problem of non-linearity will remain even with the use of digitally controlled potentiometers. However, it is possible to hide this non-linearity from the user by incorporating an additional control block between the user and the digital input. This block will accept a digital input that is proportional to the cut-off frequency to be varied and will output the binary number that is required to drive the potentiometer to the value that will result in the required cut-off frequency. Firmware or software will be required for this purpose and may not be feasible in most practical situations.

The third drawback that is associated with the approach of varying component values to alter cut-off characteristics, is the poor accuracy that can be achieved. The accuracy of the control that can be achieved by varying a component cannot be better than the accuracy of the value of the component itself. Most variable components have a higher tolerance compared to their fixed counterparts. Temperature and other ambient conditions, aging, wear, and tear all add up to contribute towards poor accuracy. As seen from equation (1), a small uncertainty in the value of R (or C) will result in a large uncertainty in the value of \( f_c \) when R (or C) is small.

In spite of the drawbacks mentioned above, the use of variable components is still the most widely used method in variable frequency filter applications.

### 3.0 Switched Capacitor Filters

Switched capacitor filters are a group of devices that are now available in monolithic form that allows their cut-off characteristics to be controlled very accurately, completely and conveniently by the frequency of an external clock. At present, an accuracy of 0.2% is not uncommon. While the switched capacitor filters are free of several inherent drawbacks associated with conventional filters they also possess several new capabilities. [Lacanette - National Semiconductor, 1991].

A switched capacitor filter is a sampled signal device, as opposed to conventional filters which are continuous time devices. The input signal is sampled at discrete instances of time and processed to produce the required filtration. The rate at which the sampling is done is directly related to the cut-off frequency of the filter and in most cases, it is a constant ratio between the two. As a result the external clock that controls the internal sampling blocks have complete control over the cut-off characteristics. External clocks of extremely high accuracy and stability are easily realizable nowadays and very accurate, consistent and repeatable filter design is therefore a reality.

It is easy to understand the principle of operation of a switched capacitor filter by referring to a conventional active filter. Active filters use resistors, capacitors and gain devices such as op-amps. The value of the resistors and capacitors determine the cut-off characteristics. In a switched capacitor filter, high-speed electronic switches replace one or more of the resistors. A switch that is turned on and off rapidly simulates a resistor whose value is related to the rate at which the switch is operated. As a result, the cut-off characteristics of the filter become a function of the switching rate.

Consider the two filter circuits shown in Figure 2. Figure 2(a) shows a simple active integrator, which can act as a low pass filter. Figure 2(b) is the switched capacitor equivalent of this filter. In the latter, the switches S1 and S2 are controlled by the clock signals (1 and 2 respectively. For simplicity let us assume both clock signals to be complementary to each other. Hence whenever S1 is OFF, S2 will be ON and vice versa.

**Figure 2. Operating Principle of a Switched Capacitor Filter**

Let us also assume that compared to the frequency of (1 and 2, Vin varies very slowly. When S1 is closed, assuming zero 'ON' resistance, the capacitor C will absorb a charge CVin almost instantaneously and charge up to voltage Vin. When S2 closes, C will be virtually grounded via the op-amp input. Since the op-amp cannot sink any current, its output will be driven to a suitable negative voltage, enabling the feedback capacitor Cf to absorb the charge CVin which was stored in capacitor C, thus enabling the latter to discharge completely.
This process will repeat for every clock cycle. If the clock period is T, then the average current flowing between the input and output will be given by,

\[ I = \frac{CV_{in}}{T} = CV_{in}f_{CLK} \quad \text{(2)} \]

Where \( f_{CLK} \) is the clock frequency.

Since the two circuits are equivalent,

\[ I = \frac{Vin}{R} \quad \text{(3)} \]

Therefore, from (2) and (3) it follows that

\[ R = \frac{1}{Cf_{CLK}} \quad \text{(4)} \]

Hence, the switches S1 and S2 are simulating the resistor R which is completely controllable through \( f_{CLK} \). By using the arrangement as an elementary building block, the switched capacitor equivalent of any active filter circuit may be easily realized. Integrated Circuits by Botkar [1994] and National semiconductor Application note 779" by Lacanette [1991] are more descriptive on this subject.

MOS switches are used to simulate the resistors in actual circuits. They have extremely low ON resistance and very high OFF resistance which approach almost ideal behaviour at practical clock frequencies. In addition, complementary switching is easily realizable.

An essential limitation of the switched capacitor filter is the higher noise level at the output. In a conventional active filter, only thermal noise will be present. In the switched capacitor filter, additional noise due to switching will be inevitable.

Although a low pass filter was used to explain the operating principle, any type of filter can be realized using the switched capacitor approach. In the case of low pass and high pass filters, the external clock controls the cut off frequency while in the case of band pass and notch filters, the external clock will control the centre frequency. All pass filters could also be realized where the phase response could be controlled via the external clock. The requirement for external components is minimum as far as the cut off characteristics are concerned.

Figure 3 illustrates the block diagram of a universal switched capacitor filter. It has separate low-pass, band pass and high pass outputs. Notch and all pass responses may be obtained by using different external resistor connections. [Lacanette 1991]

![Figure 3. Block Diagram of a Universal Switched Capacitor Filter.](image)

(Source : Application Notes, National Semiconductor Corporation)

The LMF 100, MF5 and MF10 by National Semiconductor are examples of this type of filters. The LMF40, LMF60, M4 and MF6 by National Semiconductor and the TLC04 and TLC14 by Texas Instruments are low pass Butterworth filters. The National Semiconductor MF8 is a band pass filter while the LMF90 is a notch filter whose response characteristics are logic programmable.

A typical design of a switched capacitor filter application would begin with the determination of the order of the filter required. Higher order filters can be realized by cascading several low order filters. As seen earlier, the external clock determines the cut-off frequency. Most filters support both TTL and CMOS level clocks. Chapter 9 of Integrated circuits by Botkar (1994) gives several design examples.

4.0 Merits and Drawbacks

The choice between the use of conventional active filters and the use of switched capacitor filters depend on the merits and drawbacks of the switched capacitor approach.

As mentioned earlier, higher output noise level is a major drawback of switched capacitor filters.
Since the filter is realized in IC form the on chip capacitors cannot take very high values. Hence, in order to obtain the required time constants, the value of the simulated resistors must be high, resulting in a higher level of (simulated) noise at the output. For a typical filter, the RMS noise level at the output may range from 1000V to 3000V, over a 20 kHz bandwidth.

In addition to the thermal noise of the simulated resistors, a trace of the clock frequency will also be present at the output. However, this frequency may be removed using a simple passive filter at the output.

The second major drawback of switched capacitor filters is the aliasing effect that may result due to the switching. As seen from Figure 4, whenever the input signal contains frequencies greater than half the clock frequency, the lower side band image will trespass into the required pass band.

From the designer's point of view, the ease of design using switched capacitor filters is a major advantage. In most cases, the design will be reduced to that of a clock circuit and that too as an external block. In addition, as seen from equation (4) where the simulated resistor has a capacitive term in its denominator, the product between a capacitance and this resistor in order to obtain a time constant, will result in a ratio between two capacitors. Since a ratio is more precisely controllable than individual component values, more accurate design is possible [Bokkar 1994].

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 band pass application, the presence of signals at frequencies close to the clock rate will often be acceptable because aliasing will reflect these frequencies onto the stop band of the filter [Lacanette 1991].

Offset voltage is the third drawback. Switched capacitor filter outputs have large offsets sometimes as high as 100mV and therefore are not suitable for applications requiring D.C. precision.

As for the merits of switched capacitor filters, the most obvious one is their availability in IC form. The use of MOS technology enables very high package density which in turn allows the realization of higher order filters in monolithic form.

Additional built in advantages that come with the realization of simulated resistances are the reduced power consumption, reduced temperature drift, smaller physical size and reduced tolerance. Use of monolithic resistors would have resulted in just the opposite.

Another design advantage is the reduced component count and smaller PCB area required. Conventional active filters require a resistor capacitor pair per pole. All conventional active filters require at least a single op-amp. In contrast, a switched capacitor filter of order as high as six will still be a single IC requiring very low external components.
Switched capacitor filters can easily cover a center frequency range from 0.1 Hz or less to 100 kHz or more. For a conventional filter to approach the above lower limit, large valued components will be required. At the higher end, op-amp slew rate will act as a limiting factor.

Although plagued by a higher output noise level, the switched capacitor filters exhibit surprisingly high dynamic ranges on the order of 80dB or more.

5.0 Common Applications

The accurate centre frequency and smaller PCB space make the switched capacitor filters the best choice for all types of tone detection applications, such as Fax, Modems and acoustic instrumentation.

They are also widely used for noise rejection in Biomedical instrumentation, general instrumentation and as anti-aliasing filters in data acquisition systems.

The most popular applications are those of variable frequency filtering such as Spectrum Analysis, Multiple Function Filtering and Software controlled signal processing. Frequency programmable applications also come under this category. The ability to control the external clock in any desired manner makes the switched capacitor filters the best choice for such applications.

6.0 Design Example

The design and construction of a frequency programmable low pass filter using the National Semiconductor LMF60-100 switched capacitor filter is presented here.

The design objective was to realize a programmable cut-off frequency low pass filter suitable for laboratory use, which has a user friendly front end, minimum component count and low cost.

The National Semiconductor LMF60 low pass filter was chosen for the application. The LMF60 is a 6th order Butterworth low pass filter. Butterworth filters have flat passbands, stop bands and appreciably linear phase response. However, the transition bands of Butterworth filters are wide compared to certain other types of filters. The sharpness of the transition characteristics improve with increasing order of the filter and for a sixth order filter, the transition is appreciably sharp. Hence the choice of the LMF60.

A detailed description of the LMF60 is found in the National Semiconductor Application note and data sheet on the LMF60 6th order switched capacitor Butterworth low pass filter [1996].

The upper cut-off frequency of the LMF60 LPF is controlled by a control clock input. The ratio fc/ck where fc is the control clock frequency and fc is the upper cut-off frequency, is fixed. In the LMF60-50, this ratio is internally fixed at 50. Therefore by making the control clock frequency equal to 50N Hz, where N is an integer, the cut-off frequency can be made to equal N Hz. If N could be controlled digitally, a programmable filter would result. Similarly, in the LMF60-100, the ratio fc/ck is set to 100. Therefore, in this case, to obtain a cut-off frequency equal to N Hz, the control clock frequency should be made to equal 100N Hz.

In order to enable the precise control of the cut-off frequency in very small steps, 1kHz was chosen as the smallest increment or the resolution step. Since the choice was for the LMF-100 in which fc/ck = 100, in order to vary the cut-off frequency in steps of 1kHz, it was required to vary the control clock frequency in integer multiples of 100kHz. Hence, with this choice, the design was transformed to the realization of a step variable frequency clock.

The user will control the variable frequency of the control clock by providing an integer input eN where a set of thumbwheels. It was decided to have a two digit input for eN so that the desired cut-off frequency will be N kHz, where 0≤N< 99 theoretically. This would enable the user to ideally vary the cut off frequency from 1kHz to 99 kHz, in steps of 1 kHz. This control is illustrated in Figure 5.

![Figure 5. Control of Cut-off frequency by varying the value of 'N'](image)

To implement this arrangement, it was decided to use a PLL frequency multiplier. The conceptual diagram of the multiplier that was used is shown in Figure 6.
The heart of this circuit is a stable 100 kHz, clock with TTL compatible output. This clock forms one input to the phase comparator of the PLL. The other input is derived by dividing the VCO output of the PLL by an integer N, set by the user via the thumbwheels. A programmable divider is used for this purpose. For the PLL to acquire lock with the incoming clock frequency of 100kHz, the output of the programmable divider should also become equal to 100kHz, which will occur only when the input to the divider becomes equal to 100N kHz. Hence the phase detector output will drive the VCO until the VCO output stabilizes at 100N kHz, which happens to be the required control clock frequency itself.

When the 100N kHz control clock is given to the LMF60-100, where fcl/fc ratio is 100, the LMF60-100 becomes a low pass filter with cut off frequency N kHz. Hence the user can directly program the cut-off frequency by simply selecting the value of N without having any need to derive the required inputs by calculation.

When the two digit thumbwheel setting equals N (where 0 < N < 99), in order to have the cut off frequency sharply at N kHz, it is essential that the clock frequency should be precisely 100N kHz. Since N is always an integer, all that is necessary to ensure that the control clock frequency is precisely 100N kHz is to ensure that the oscillator is running precisely at 100 kHz. In order to obtain this precision, a crystal oscillator is recommended. Figure 7 shows the schematic of a 100 kHz crystal oscillator that could be used for this purpose. However, a simple 100 kHz astable circuit constructed using a 555 timer worked satisfactorily for demonstration purposes.

Figure 7. 100kHz Crystal Oscillator

Since N is varied between 1 and 99, the VCO output of the PLL will be swept from 100 kHz to 9900 kHz, in steps of 100 kHz. This would be the ideal sweep range of the VCO of the PLL. However, the maximum upper cut-off frequency that can be obtained by the LMF60-100 is 30 kHz. Therefore, the required range is limited to 100kHz - 3MHz. In addition, a limitation in the CMOS counter sets the lower limit of N to be 3. Therefore, the range is further limited to 300kHz - 3MHz. Accordingly, the PLL needs to be able to sweep only this range.

The HEF4046B CMOS PLL was chosen for this purpose. Using a 7V and external components to set a center frequency of 1MHz, it was possible to obtain a sufficient lock range, which enabled the use of N up to 22, and thereby to obtain a cut-off frequency up to 22kHz.

The remaining block is the programmable divider itself. Since a two-digit divider was required, the HEF4059B CMOS fully programmable divide by N counter was selected.

The HEF 4059B counter is capable of providing an integer division in the range from 3 to 15999. The divider value N is set using 16 Jam inputs, allowing a 4-digit value for N. However, since only two digits were required, the two thumbwheels were used to directly drive the 8 least significant jam inputs with all others jam inputs grounded, resulting in a two digit programmable divider. Figure 8 shows the implementation of the divider.
Figure 8. Two digit programmable divider

Figure 9 illustrates the results of one of the performance tests carried out on the Frequency programmable filter designed and constructed as described above.

If this filter is to be constructed for actual laboratory use or if it is required to produce it on a large scale, several improvements are possible.

i. The most important improvement is the replacement of the 555 timer based 100kHz astable by a 100kHz crystal clock. Since the cut-off frequency is a direct function of this clock frequency, its accuracy is most important.

ii. In order to make the user interface much more convenient, several improvements could be made. For instance, the thumbwheels could be replaced by a simple electronic numeric keypad with an LED display for input indication. The facility could also be provided to store and recall previous inputs. Even a non-volatile memory could be provided.

iii. If it is required to sweep the cut-off frequency over a range, a counter could be used in place of the thumbwheel switches. When the counter is counting up or down, the divisor &N of the programmable divider will vary in a staircase man-
ner, causing the control clock also to vary in a staircase manner. This will cause the cut-off frequency of the filter to sweep up or down within a given range.

iv. If it is required to control the filter through a computer, all that is necessary is to provide an interface parallel with the thumbwheels or the keypad, that would enable the loading of the value εNi from the computer.

v. If more sharpness in the filter cut-off characteristics is desired, two LMF60s could be cascaded together. It is for this reason that the IC has been produced to operate at unity gain within the passband. The same clock should drive both the cascaded filters.

The design of this filter heavily relies on the proper operation of the switched capacitor filter, the LMF60. The datasheets indicate that the fekl/fc ratio is susceptible to power supply fluctuations and variations in temperature. These factors will cause the filter to deviate from ideal behaviour.

The LMF60 series are all 6th order filters. Hence it is not suitable for closed loop applications. Any system, which has more than two poles in its open loop transfer function, may become unstable under closed loop conditions even when the feedback is negative. This should be borne in mind when using this filter in applications.

7.0 Conlusion

The cut-off characteristics of switched capacitor filters are completely controllable through an external clock. Therefore they are ideal for cut-off frequency programmable filter applications. They also offer several additional advantages. The availability in monolithic form, improved temperature stability, precision of the cut-off frequency, ease of cascading to increase the order of the filter are some of these. The inherent drawback is the higher noise level at the output.

The design example illustrated how a switched capacitor filter can be used as a single separate block in a useful application.

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