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Electronically Tunable Third-Order Switched-Capacitor Filter with Feedforward Signal to Minimize Overshoot

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Abstract- The study proposes an Electronically Tunable Third-Order Switched-Capacitor Filter with Feedforward Signal to minimize Overshoot Configuration. This circuit is designed for center frequency f_0=15 KHz. The proposed circuit discusses a new configuration to realize third-order with three filter functions low-pass, band-pass, and high- pass simultaneously in single circuit. The circuit uses OP-AMP and MOSFET with Capacitor as Switched-Capacitor. The response of circuit is studied for different circuit merit factor Q and center frequency f_0=15 KHz. The filter circuit can be used for both narrow as well as for wide bandwidth, Also, this circuit works for electronically tunable bandwidth. The gain roll-off for this circuit is close to the ideal value of 18 dB / octave (40dB/ decade) as for third order filters. This filter configuration shows better response for Q ≥ 0.4. Also, stabilization of gain for High - pass filter function can be achieved at 0dB for Q≥0.4. In the proposed circuit configuration, the peak gain for overshoot is minimizing from 44dB to 5dB due to the feedforward input signal. The Low-pass filter function works practically only for higher merit factor Q. The circuit shows better response for Q≥ 0.4 and f_0 =15 kHz.

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Electronically Tunable Third-Order Switched-Capacitor Filter with Feedforward Signal to Minimize Overshoot

Adnan Abdullah Qasem [α] & G. N. Shinde [σ]

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I. Introduction

Conventional analog circuits use the ratio of resistances to set the transfer function of filter circuits. The values of RC product determine the frequency responses of these circuits [1-2]. A switched-capacitor can replace a resistor [2]. MOSFET technology can be used for designing switched-capacitor circuits [3]. The filter circuits using Switched-Capacitor allow very sophisticated, accurate and tunable analog circuits to be manufactured. Many of the circuits proposed the working of only one type of operation [5- 10]. The Switched-Capacitor concept can be used to realize wide variety of universal filter that have the advantage of compactness and tenability [5]. Switched capacitor techniques have been developed so that both digital and analog functions can be integrated on a single silicon chip. 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% foremost Switched-Capacitor ICs, and worst-case numbers range from 0.4% to 1.5% (assuming, of Course, that an accurate clock is provided) [6]. This Paper of Electronically Tunable Third-Order Switched-Capacitor Filter with Feedforward Signal to minimize Overshoot has been studied for different values of circuit merit factor Q and f_0=15 KHz .

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II. Basic Switching Operation

The essence of the Switched-Capacitor is the use of Capacitors and analog Switches to perform the same function as resistors. This replacement of resistor, analog with op. amp based integrator, and then forms an active filter. Furthermore, the use of the Switched-Capacitor will be seen to give frequency tenability to active filters. Filter using Switched-Capacitor technique overcome a major obstacle of filter on a chip fabrication—the implementation of resistors by simulating resistors with high speed Switched-Capacitors using MOSFETs. The switching function of the MOSFET produces a discrete response rather than a continuous response from the filter [14]. The operation of switched-capacitor can be explained with the help of following circuit diagram.

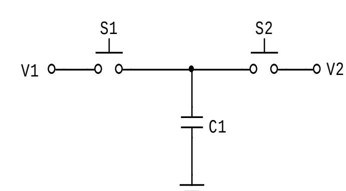

Figure 1 : Circuit diagram for operation of the switched-capacitor

Since the charge q on a capacitor C_1 is given by

$$q = C_1 V$$

Where V is the voltage across the capacitor C_1.

Therefore, when S_2 closes with S_1 open, then S_1 closes with S_2 open a charge q is transferred from V_2 to V_1 with

$$\Delta q = C_1 \ (V_2 - V_1)$$

If this switching process is repeated N times in time (t), then the amount of charge transferred per unit time is given by

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$$\frac{\Delta q}{\Delta t} = C_1(V_2 - V_1)\frac{N}{\Delta t}$$

L.H.S. is current and number of cycles per unit time is switching frequency.

$$\therefore i = C_1(V_2 - V_1)\, f_{clk}$$

$$\therefore \frac{(V_2 - V_1)}{i} = \frac{1}{C_1 f_{clk}} = R$$

Thus the switched-capacitor is equivalent a resistor.

III. Proposed Circuit Configuration

The proposed circuit configuration for Electronically Tunable Third-Order Switched-Capacitor Filter with Feedforward Signal to minimize Overshoot is shown in Figure 2. The circuit consists of three op–amps (μA 741) with wide identical gain bandwidth product (GB) and four Capacitors with MOSFET, which form Switched-Capacitor. Switched-Capacitor can replace resistors, which was proposed earlier [2]. The input sinusoidal voltage is applied to the inverting terminal of the first op-amp through switched capacitor (SC). The non-inverting terminal is grounded. SC is used in the feedback circuit. The output of the first op-amp is supplied as non-inverting input of the second op-amp. The feedforward input signal is given to the inverting terminal of the second op-amp. SC is used as feedback. The output of the second op-amp is supplied as non-inverting input of the third op-amp. The inverting terminal is grounded. SC is used as feedback. Low-pass function is observed at the output of the third op-amp. The output of the second op-amp gives Band-pass function. The High-pass function is seen at the inverting input of the first op-amp.

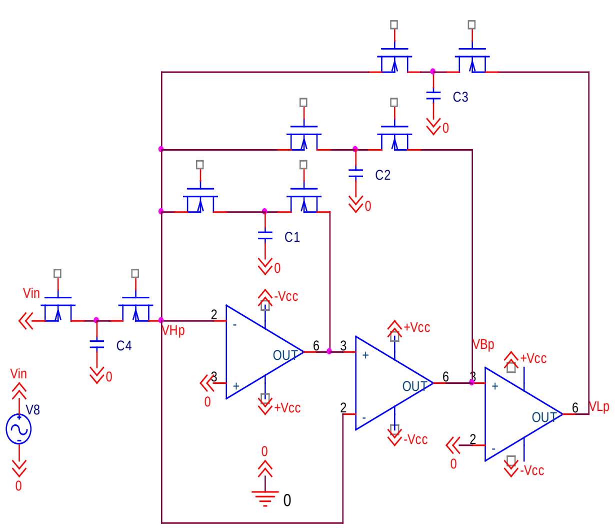

Figure 2 : Proposed Circuit diagram for Electronically Tunable Third Order Switched-Capacitor filter

IV. Circuit Analysis and Design Equations

Op-amp (μA 741) is an internally compensated op-amp, which represented by "Single pole model",

$$A(s) = A_0\omega_0 / (S + \omega_0) \tag{1}$$

Where,

A_0 = open loop d.c. gain, ω_0 = open loop -3dB bandwidth, GB = $A_0\,\omega_0$ = gain bandwidth product of op-amplifier.

$$A(s) = A_0\omega_0 / S = GB / S, \tag{2}$$

Where, $S >> \omega_0$

This shows that the op-amplifier is an "integrator", Thus Electronically Tunable Third-Order Switched-Capacitor Filter transfer function at three different terminals are given below. The voltage transfer function for low-pass filter:

$$T_{Lp} = \frac{-GB_1 GB_2 GB_3 C_4}{X_1 S^3 + X_2 S^2 + X_3 S + X_4} \tag{3}$$

The voltage transfer function for band-pass filter:

$$T_{Bp} = \frac{-S GB_1 GB_2 C_4}{X_1 S^3 + X_2 S^2 + X_3 S + X_4} \tag{4}$$

The voltage transfer function for high-pass filter:

$$T_{Hp} = \frac{S^3 C_4}{X_1 S^3 + X_2 S^2 + X_3 S + X_4} \tag{5}$$

Where

$X_1 = C_1 + C_2 + C_3 + C_4$

$X_2 = GB_1 C_1 + GB_2 C_2$

$X_3 = GB_1 GB_2 C_2 + GB_2 GB_3 C_3$

$X_4 = GB_1 GB_2 GB_3 C_3$

The circuit was designed using coefficient matching technique i.e. by comparing these transfer functions with General Third-order transfer functions [10]. The general Third-order transfer function is given by

$$T(S) = \frac{\alpha_3 S^3 + \alpha_2 S^2 + \alpha_1 S + \alpha_0}{S^3 + \omega_0\left(1 + \frac{1}{Q}\right)S^2 + \omega_0^2\left(1 + \frac{1}{Q}\right)S + \omega_0^3} \tag{6}$$

By comparing (3), (4), and (5) with (6), we get the design equation as

$$C_1 + C_2 + C_3 + C_4 = 1 \tag{7}$$

$$GB_1 C_1 + GB_2 C_2 = W_0\,\{1 + 1/Q\} \tag{8}$$

$$GB_1 GB_2 C_2 + GB_2 GB_3 C_3 = W_0^2\,\{1 + 1/Q\} \tag{9}$$

$$GB_1 GB_2 GB_3 C_3 = W_0^3 \quad (10)$$

So that Values of C_1 , C_2 , C_3 and C_4 can be calculated using these equations for different values of Q and f_0 =15 KHz (table1).

Table 1 : Capacitance values for different values of Q

Q	C_1(µf)	C_2(µf)	C_3(nf)	C_4(µf)
0.1	286.8	7.9	19.2	705.3
0.4	91.3	2.5	19.2	906.2
0.8	58.7	1.6	19.2	939.7
1	52.2	1.4	19.2	946.4
4	32.6	0.9	19.2	966.5
8	29.3	0.8	19.2	909.8
10	28.7	0.77	19.2	970.5

V. Sensitivity

The sensitivities of ω_0 and Q in this Electronically Tunable third-order Switched-capacitor Filter are as follows.

$$S_{C_1}^{W_0} = -\frac{1}{3} C_1$$

$$S_{C_2}^{W_0} = -\frac{1}{3} C_2$$

$$S_{C_3}^{W_0} = -\frac{1}{3}\{C_3 - 1\}$$

$$S_{C_4}^{W_0} = -\frac{1}{3} C_4$$

$$S_{GB_1}^{W_0} = S_{GB_2}^{W_0} = S_{GB_3}^{W_0} = \frac{1}{3}$$

$$S_{C_1}^{Q} = -\frac{1}{3}(1+Q)C_1$$

$$S_{C_2}^{Q} = -(1+Q)C_2\left\{\frac{1}{(C_2+C_3)} - \frac{1}{3}\right\}$$

$$S_{C_3}^{Q} = -(1+Q)\left\{\frac{1}{(C_2+C_3)} - \frac{1}{3} - \frac{2}{3C_3}\right\}$$

$$S_{C_4}^{Q} = -\frac{1}{3}(1+Q)\,C_4$$

$$S_{GB_1}^{Q} = -(1+Q)\left\{\frac{C_2}{C_2+C_3} - \frac{2}{3}\right\}$$

$$S_{GB_2}^{Q} = -\frac{1}{3}(1+Q)$$

$$S_{GB_3}^{Q} = -(1+Q)\left\{\frac{C_3}{C_2+C_3} - \frac{2}{3}\right\}$$

VI. Experimental Set Up

The circuit consists of three op–amps (µA 741) with wide identical gain bandwidth product (GB) and four Capacitors with MOSFET, which form Switched-Capacitor. The circuit performance is studied for different Values of circuit merit factor Q with center frequency f_0=15 KHz. The general operating range of this filter is 10 Hz to 1.2 MHz The value of GB (GB_1=GB_2=GB_3) is ($2\pi \times (5.6) \times 10^5$ rad/sec). The table1 shows the capacitor values for different circuit merit factor Q. MOSFETs are driven by two non-overlapping clocks. The input voltage of 0.5mV is applied. The table1 shows the capacitor values for different circuit merit factor Q.

VII. Result and Discussion

Following observations are noticed for Low-pass, Band-pass and High-pass at corresponding terminals.

a) Low-Pass Response

The figure 3 shows the low pass response for different values of circuit merit factor Q.

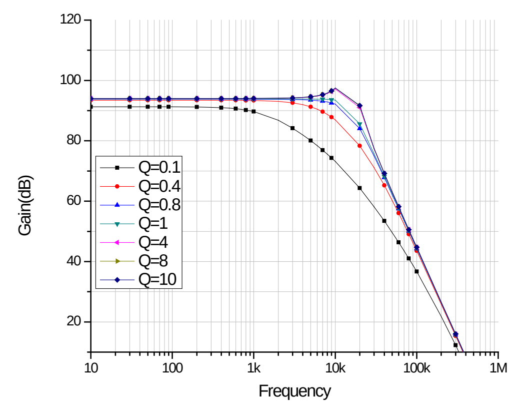

Figure 3 : Low-pass (LP) responses for different values of Q

Table 2 : Analysis of Low Pass Response for Graph (Fig. 3)

Q	Max. Passband Gain (dB)	f_{0L} (kHz)	$f_0 \sim f_{0L}$ (kHz)	Gain Roll-off in stop band	
				dB/Octave (kHz)	Octave starting at (kHz)
0·1	91.3	20	5	17	215
0·4	93.4	38	23	17.7	90
0.8	93.6	43	28	18	60
1	93.8	43	28	18	60
4	94	44	29	18	60
8	94	44	29	18	60
10	94	44	29	18	60

The maximum pass-band gain varies between 91.3dB to 94dB and the gain roll-off per octave varies between 17 to 18dB/octave. But in previous reported configuration maximum pass-band gain varies between 82dB to 87dB. Also, the gain roll-off per octave in stop-band varies between 14 to 19dB/octave [14]. The maximum pass-band gain increase with increase in values of circuit merit factor Q but after Q≥4 this value gets stabilized at the maximum pass-band gain. The Gain roll-off values are close to ideal value of 18dB/octave for third order switched-capacitor filter. The response shows no overshoot for all the values of circuit merit factor Q where as the previous reported configuration shows overshoot with increase in Q (for Q=10, the overshoot is 14 dB) [14].

b) High-pass response

The figure 4 shows the High pass response for different values of circuit merit factor Q.

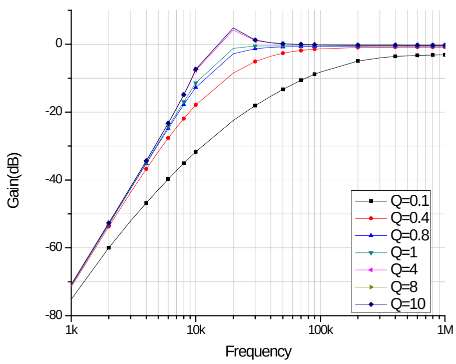

Figure 4 : High-pass (HP) responses for different values of Q

Table 3 : Analysis of High Pass Response for Graph (Fig. 4)

Q	f_{0H}(kHz)	$f_0 \sim f_{0H}$(kHz)	Gain Roll-off in stop band		Gain Stabilization		Peak Gain of overshoot (dB)
			dB/Octave	Octave Starting at (kHz)	(dB)	f_S(kHz)	
0.1	158	143	17.4	2	-3	460	0
0.4	37	22	18	3.5	0	170	0
0.8	19	4	18	5	0	46	0
1	13	2	18	5	0	46	0
4	13	2	18	5	0	40	3
8	13	2	18	5	0	40	5
10	13	2	18	5	0	40	5

The Gain roll-off in stop-band varies between 17.4dB to 18dB/octave which is close to the ideal value of 18 dB /octave for third order Switched-Capacitor filter .Also, the gain is stabilized for all values of circuit merit factor Q ≥ 0.4 . But in previous reported Configuration, the Gain roll-off in stop-band varies between 11 to 12dB/octave. Also, the gain can't be stabilized at 0dB for all values of circuit merit factor Q [14]. The peak gain for overshoot is minimizing from 44dB to 5dB due to the feedforward input signal that's given to the second Op-amp in the proposed circuit configuration. The gain gets stabilized almost at 0 dB for all values of Q ≥ 0.4. The response shows overshoot for all the values of Q ≥ 4. The analysis for the responses are summarizes in the table 3.

Table 4 : Comparison of Overshoot

Overshoot observed in dB		
Q	Previous Reported circuit	Proposed circuit
0.1	0	0
1	0	0
5	38	3
10	44	5

c) Band-pass response

The figure 5 shows the Band-pass response for different values of circuit merit factor Q.

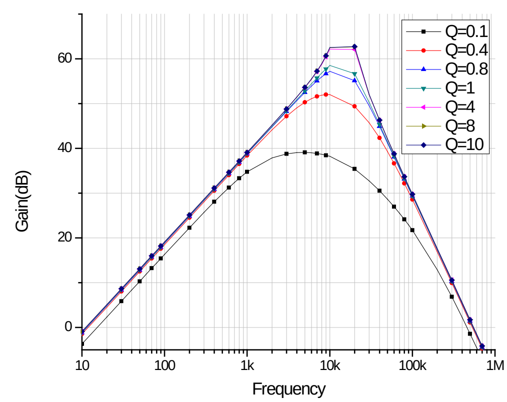

Figure 5 : Band-pass (BP) response for different values of Q

Table 5 : Analysis of Band Pass Response for Graph (Fig. 5)

Q	Max. Passband gain (dB)	f_1 (kHz)	f_2 (kHz)	BW (kHz)	Gain Roll-off / octave in stop band			
					Leading Part		Trailing Part	
					dB/ octave	Octave starting at (kHz)	dB/ octave	Octave starting at (kHz)
0·1	39	0.4	55	54.6	5.8	0.6	12	206
0·4	52	0.8	60	59.2	6	3	12	61
0.8	57	1.2	52	51.8	6	3	12	40
1	58	1.3	51	50.7	6	3	12	41

4	62	1.7	44	43.2	6	3	12	41
8	62.5	1.8	44	43.2	6	3	12	41
10	62.5	1.8	44	43.2	6	3	12	41

The maximum pass-band gain varies between 39dB to 62.5dB. Also, the bandwidth varies between 43.2 KHz to 59.2 KHz and Gain roll-off in trailing part varies between 11.6 to 12dB/octave. But in previous reported configuration the maximum pass-band gain varies between 33dB to 73dB.Also, the bandwidth varies between 59.4 KHz to 22 KHz and Gain roll-off in trailing part varies between 8dB/octave to 13dB/octave [14]. The maximum pass-band gain increases with increase in circuit merit factor Q. The bandwidth decreases with increasing in values of circuit merit factor Q but after $Q \geq 4$ this value gets stabilized at 43.2 KHz. For lower values of circuit merit factor Q, this filter can be used for wide bandwidth and for higher values of circuit merit factor Q it can be used for narrow bandwidth. There is no shift in the central frequency. It is also observed that the pass band distribution of frequency is symmetric for both sides. The gain roll-off/octave in leading and trailing part of the response is same. The circuit works better band pass response for $Q \geq 0.4$.

VIII. Conclusions

A realization of Electronically Tunable Third-Order Switched-Capacitor Filter with Feedforward Signal to minimize Overshoot has been proposed. The filter circuit can be used for both narrow as well as for wide bandwidth, so this circuit works for electronically tunable bandwidth. The gain roll-off for this circuit is close to the ideal value. The gain gets stabilized almost at 0 dB for all values of $Q \geq 0.4$.The Low pass filter function works practically only for higher merit factor Q. The circuit shows better response for $Q \geq 0.4$ and $f_0 = 15$ kHz. In the proposed circuit configuration, the peak gain for overshoot is minimizing from 44dB to 5dB due to the feedforward input signal.

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