THE TOTAL CAPACITANCE, TRANSIENT AND FREQUENCY RESPONSES OF MFB, FDNR AND LEAPFROG TECHNIQUES FOR BILINEAR SWITCHED — CAPACITOR NETWORK

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ABSTRACT

A comparison for bilinear switched-capacitor (SC) filter realization based on various approach techniques is made and the transient response, frequency and total capacitance of the designed filter are presented. The simulation results and conclusions obtained can serve as useful guidelines in choosing suitable designs for bilinear SC structure in accordance to the nature of the filter problems.

1. INTRODUCTION

One method to get high order filter is by cascading passive LC or active RC ladder networks, where R, L and C represent the resistor, inductor and capacitor elements. The same method can also be used to realize SC network. Many factors such as the type of integration and transformation have to be considered in the design of the SC filter. For example, the bilinear SC filters can be realized with active integration of biquad RC and SC.

The biquad network consists of a single operational amplifier as an infinite-gain voltage amplifier and two or more components that provide negative feedback. This arrangement of biquad is called the Multiple-Feedback (MFB)¹⁻³.

The SC filter can also be obtained by simulating the voltage and current of passive ladder structure with analog operation such as RC integration. This approach is called the Leapfrog technique⁴⁻⁸.

Next, the transformation technique is applied in the LC network where resistor, inductor and capacitor will be transformed to capacitor, resistor and a new building block respectively. This new building block will be presented with a positive real constant which is called D. This technique is known as Frequency — Dependent Negative Resistor (FDNR)⁸⁻¹¹.

2. PERFORMANCE FOR SWITCHED-CAPACITOR

Generally, the performance of various SC design techniques can be evaluated based on the following criteria:

- (a) to create reference system with optimum design and excellent response.
- (b) to obtain fundamental criteria system such as transient response, frequency and stability.

3. THE VARIATIONS OF BILINEAR SWITCHED-CAPACITOR FILTER CONFIGURATION

Tables 1, 2 and 3 show the component values that are used in the circuit for each bilinear SC filter. The common circuits for communication systems used for bilinear MFB, Leapfrog and FDNR SC networks are shown in Figure 1. All of the above SC designs are based on LC and RC networks.

Table 1: Component values of various low pass switched-capacitor design at Cutoff Frequency 10 kHz for 5th-order.

MFB	LEAPFROG	FDNR
$C_4 = 0.048 \times 10^{-12}$	$C_1 = 1.00 \times 10^{-12}$	$C_1 = 20.00 \times 10^{-9}$
$C_5 = 1 \times 10^{-12}$	$C_2 = 9.843 \times 10^{-13}$	$C_{2m} = 5.08 \times 10^{-9}$
$C_{r1} = 0.0245 \times 10^{-12}$	$C_3 = 1.00 \times 10^{-12}$	$C_a = 32.3 \times 10^{-9}$
$C_{r2} = 0.0245 \times 10^{-12}$	$C_4 = 1.00 \times 10^{-12}$	$C_{4m} = 1.25 \times 10^{-9}$
$C_{r3} = 0.0489 \times 10^{-12}$	$C_5 = 257 \times 10^{-12}$	$C_{5m} = 1.25 \times 10^{-9}$
$C_9 = 0.327 \times 10^{-12}$	$C_6 = 1.00 \times 10^{-12}$	$C_{6m} = 3.14 \times 10^{-9}$
$C_{10} = 1 \times 10^{-12}$	$C_7 = 3.180 \times 10^{-12}$	$C_b = 20.00 \times 10^{-9}$
$C_{r4} = 0.064 \times 10^{-12}$	$C_8 = 1.00 \times 10^{-12}$	$C_{8m} = 1569 \times 10^{-9}$
$C_{r5} = 0.064 \times 10^{-12}$	$C_9 = 257 \times 10^{-12}$	$C_c = 32.3 \times 10^{-9}$
$C_{r6} = 0.1281 \times 10^{-12}$	$C_{10} = 1.00 \times 10^{-12}$	$C_{9m} = 1.25 \times 10^{-9}$
$C_{13} = 1 \times 10^{-12}$	$C_{11} = 9.843 \times 10^{-12}$	$C_{10m} = 1.25 \times 10^{-9}$
$C_{r7} = 0.079 \times 10^{-12}$	$C_{12} = 1.00 \times 10^{-12}$	$C_{11m} = 3.14 \times 10^{-9}$
$C_{r8} = 0.158 \times 10^{-12}$		$C_d = 20.00 \times 10^{-9}$
		$C_{13m} = 5.08 \times 10^{-9}$

Table 2: Component values of various low pass switched-capacitor design at Cutoff Frequency 10 kHz for 10th-order.

MFB		LEAPFROG		FDNR	
$C_4 = 0.012 \times 10^{-12}$	$C_{19} = 0.397 \times 10^{-12}$	$C_1 = 1.00 \times 10^{-12}$	$C_{12} = 1.000 \times 10^{-12}$	$C_1 = 20.00 \times 10^{-9}$	$C_{17m} = 6.25 \times 10^{-10}$
$C_5 = 1 \times 10^{-12}$	$C_{20} = 1 \times 10^{-12}$	$C_2 = 9.960 \times 10^{-13}$	$C_{13} = 6.287 \times 10^{-12}$	$C_{2m} = 5.02 \times 10^{-9}$	$C_{18m} = 1.571 \times 10^{-9}$
$C_{r1} = 0.0062 \times 10^{-12}$	$C_{r16} = 0.0351 \times 10^{-12}$	$C_3 = 1.00 \times 10^{-12}$	$C_{14} = 1.000 \times 10^{-12}$	$C_a = 1.82 \times 10^{-8}$	$C_f = 20.00 \times 10^{-9}$
$C_{r2} = 0.0062 \times 10^{-12}$	$C_{r17} = 0.0351 \times 10^{-12}$	$C_4 = 1.00 \times 10^{-12}$	$C_{15} = 5.672 \times 10^{-12}$	$C_{4m} = 6.25 \times 10^{-10}$	$C_{20m} = 8.814 \times 10^{-10}$
$C_{r3} = 0.0123 \times 10^{-12}$	$C_{r18} = 0.0701 \times 10^{-12}$	$C_5 = 2.890 \times 10^{-12}$	$C_{16} = 1.000 \times 10^{-12}$	$C_{5m} = 6.25 \times 10^{-10}$	$C_g = 2.83 \times 10^{-8}$
$C_9 = 0.103 \times 10^{-12}$	$C_{24} = 0.488 \times 10^{-12}$	$C_6 = 1.00 \times 10^{-12}$	$C_{17} = 4.501 \times 10^{-12}$	$C_{6m} = 1.571 \times 10^{-9}$	$C_{22m} = 6.25 \times 10^{-10}$
$C_{10} = 1 \times 10^{-12}$	$C_{25} = 1 \times 10^{-12}$	$C_7 = 4.500 \times 10^{-12}$	$C_{18} = 1.000 \times 10^{-12}$	$C_b = 20.00 \times 10^{-9}$	$C_{23m} = 6.25 \times 10^{-10}$
$C_{r6} = 0.0178 \times 10^{-12}$	$C_{r21} = 0.0387 \times 10^{-12}$	$C_8 = 1.000 \times 10^{-12}$	$C_{19} = 2.890 \times 10^{-12}$	$C_{8m} = 1.111 \times 10^{-9}$	$C_{24m} = 1.571 \times 10^{-9}$
$C_{r7} = 0.0178 \times 10^{-12}$	$C_{r22} = 0.0387 \times 10^{-12}$	$C_9 = 5.672 \times 10^{-12}$	$C_{20} = 1.000 \times 10^{-12}$	$C_c = 3.56 \times 10^{-8}$	$C_h = 20.00 \times 10^{-9}$
$C_{r8} = 0.0357 \times 10^{-12}$	$C_{r23} = 0.077 \times 10^{-12}$	$C_{10} = 1.000 \times 10^{-12}$	$C_{21} = 9.960 \times 10^{-13}$	$C_{10m} = 6.25 \times 10^{-10}$	$C_{26m} = 1.730 \times 10^{-9}$
$C_{14} = 0.333 \times 10^{-12}$		$C_{11} = 6.287 \times 10^{-12}$	$C_{22} = 1.000 \times 10^{-12}$	$C_{11m} = 6.25 \times 10^{-10}$	$C_i = 6.25 \times 10^{-9}$
$C_{15} = 1 \times 10^{-12}$				$C_{12m} = 1.571 \times 10^{-9}$	$C_{28m} = 6.25 \times 10^{-10}$
$C_{r11} = 0.0186 \times 10^{-12}$				$C_d = 20.00 \times 10^{-9}$	$C_{29m} = 6.25 \times 10^{-10}$
$C_{r12} = 0.0371 \times 10^{-12}$				$C_{14m} = 7.953 \times 10^{-10}$	$C_{30m} = 1.571 \times 10^{-9}$
$C_{r13} = 0.0556 \times 10^{-12}$				$C_e = 3.95 \times 10^{-8}$	$C_j = 20.00 \times 10^{-9}$
				$C_{16m} = 6.25 \times 10^{-10}$	$C_L = 20.00 \times 10^{-9}$

Table 3: Component values of various low pass switched-capacitor design at Cutoff Frequency 10 kHz for 15th-order.

MFB		LEAPFROG			FDNR	
$C_4 = 0.0055 \times 10^{-12}$	$C_{24} = 0.325 \times 10^{-12}$	$C_1 = 1.00 \times 10^{-12}$	$C_{17} = 1.270 \times 10^{-11}$	$C_1 = 20.00 \times 10^{-9}$	$C_{24m} = 7.85 \times 10^{-10}$	
$C_5 = 1 \times 10^{-12}$	$C_{25} = 1 \times 10^{-12}$	$C_2 = 1.330 \times 10^{-12}$	$C_{18} = 1.000 \times 10^{-12}$	$C_{2m} = 3.76 \times 10^{-9}$	$C_h = 20.00 \times 10^{-9}$	
$C_{r1} = 0.00205 \times 10^{-12}$	$C_{r21} = 0.0158 \times 10^{-12}$	$C_3 = 1.00 \times 10^{-12}$	$C_{19} = 1.250 \times 10^{-11}$	$C_a = 1.236 \times 10^{-8}$	$C_{26m} = 4.01 \times 10^{-10}$	
$C_{r2} = 0.00205 \times 10^{-12}$	$C_{r22} = 0.0158 \times 10^{-12}$	$C_4 = 1.00 \times 10^{-12}$	$C_{20} = 1.000 \times 10^{-12}$	$C_{4m} = 3.13 \times 10^{-10}$	$C_i = 3.66 \times 10^{-8}$	
$C_{r3} = 0.0411 \times 10^{-12}$	$C_{r23} = 0.0317 \times 10^{-12}$	$C_5 = 3.940 \times 10^{-12}$	$C_{21} = 1.170 \times 10^{-11}$	$C_{5m} = 3.13 \times 10^{-10}$	$C_{28m} = 3.13 \times 10^{-10}$	
$C_9 = 0.048 \times 10^{-12}$	$C_{29} = 0.419 \times 10^{-12}$	$C_6 = 1.00 \times 10^{-12}$	$C_{22} = 1.000 \times 10^{-12}$	$C_{6m} = 7.85 \times 10^{-10}$	$C_{29m} = 3.13 \times 10^{-10}$	
$C_{10} = 1 \times 10^{-12}$	$C_{30} = 1 \times 10^{-12}$	$C_7 = 6.360 \times 10^{-12}$	$C_{23} = 1.030 \times 10^{-11}$	$C_b = 20.00 \times 10^{-9}$	$C_{30m} = 7.85 \times 10^{-10}$	
$C_{r6} = 0.00606 \times 10^{-12}$	$C_{r26} = 0.0179 \times 10^{-12}$	$C_8 = 1.000 \times 10^{-12}$	$C_{24} = 1.000 \times 10^{-12}$	$C_{8m} = 7.86 \times 10^{-10}$	$C_j = 20.00 \times 10^{-9}$	
$C_{r7} = 0.00606 \times 10^{-12}$	$C_{r27} = 0.0179 \times 10^{-12}$	$C_9 = 8540 \times 10^{-12}$	$C_{25} = 8540 \times 10^{-11}$	$C_c = 2.64 \times 10^{-8}$	$C_{32m} = 4.85 \times 10^{-10}$	
$C_{r8} = 0.0121 \times 10^{-12}$	$C_{r28} = 0.0360 \times 10^{-12}$	$C_{10} = 1.000 \times 10^{-12}$	$C_{26} = 1.000 \times 10^{-12}$	$C_{10m} = 3.13 \times 10^{-10}$	$C_k = 2.68 \times 10^{-8}$	
$C_{14} = 0.125 \times 10^{-12}$	$C_{34} = 0.478 \times 10^{-12}$	$C_{11} = 1.030 \times 10^{-11}$	$C_{27} = 6.360 \times 10^{-12}$	$C_{11m} = 3.13 \times 10^{-10}$	$C_{34m} = 3.13 \times 10^{-10}$	
$C_{15} = 1 \times 10^{-12}$	$C_{35} = 1 \times 10^{-12}$	$C_{12} = 1.000 \times 10^{-12}$	$C_{28} = 1.000 \times 10^{-12}$	$C_{12} = 7.85 \times 10^{-10}$	$C_{35m} = 3.13 \times 10^{-10}$	
$C_{r11} = 0.00983 \times 10^{-12}$	$C_{r31} = 0.0192 \times 10^{-12}$	$C_{13} = 1.170 \times 10^{-11}$	$C_{29} = 3.940 \times 10^{-12}$	$C_d = 20.00 \times 10^{-9}$	$C_{36m} = 7.85 \times 10^{-10}$	
$C_{r12} = 0.00983 \times 10^{-12}$	$C_{r32} = 0.0192 \times 10^{-12}$	$C_{14} = 1.000 \times 10^{-12}$	$C_{30} = 1.000 \times 10^{-12}$	$C_{14m} = 4.85 \times 10^{-10}$	$C_l = 20.00 \times 10^{-9}$	
$C_{r13} = 0.01966 \times 10^{-12}$	$C_{r33} = 0.0383 \times 10^{-12}$	$C_{15} = 1.250 \times 10^{-11}$	$C_{31} = 1.330 \times 10^{-12}$	$C_e = 3.66 \times 10^{-8}$	$C_{38m} = 7.86 \times 10^{-10}$	
$C_{19} = 0.224 \times 10^{-12}$	$C_{38} = 1 \times 10^{-12}$	$C_{16} = 1.000 \times 10^{-12}$	$C_{32} = 1.000 \times 10^{-12}$	$C_{16m} = 3.13 \times 10^{-10}$	$C_m = 1.236 \times 10^{-8}$	
$C_{20} = 1 \times 10^{-12}$	$C_{r36} = 0.0196 \times 10^{-12}$			$C_{17} = 3.13 \times 10^{-10}$	$C_{40m} = 3.13 \times 10^{-10}$	
$C_{r16} = 0.0132 \times 10^{-12}$	$C_{r37} = 0.0393 \times 10^{-12}$			$C_{18m} = 7.85 \times 10^{-10}$	$C_{41m} = 3.13 \times 10^{-10}$	
$C_{r17} = 0.0132 \times 10^{-12}$				$C_f = 20.00 \times 10^{-9}$	$C_{42m} = 7.85 \times 10^{-10}$	
$C_{r18} = 0.0263 \times 10^{-12}$				$C_{20m} = 4.01 \times 10^{-10}$	$C_n = 20.00 \times 10^{-9}$	
				$C_g = 3.98 \times 10^{-8}$	$C_{44m} = 3.76 \times 10^{-9}$	
				$C_{22m} = 3.13 \times 10^{-10}$	$C_L = 20.00 \times 10^{-9}$	
				$C_{23m} = 3.13 \times 10^{-10}$		

4. DEVICE, TOTAL CAPACITANCE AND FREQUENCY SAMPLING COMPARISON

The fundamental structure of an SC filter consists of the operational amplifier, capacitor and Metal-Oxide-Semiconductor (MOS) switches. The total numbers of these devices will affect the silicon area that is to be used in the integrated circuit. If less number of total devices is used the size of the filter is smaller. The distribution for the above devices, total capacitance and frequency sampling of each SC design technique are shown in Table 4.

5. SIMULATION RESULTS

Three techniques, which are MFB, Leapfrog and FDNR, have been used to design the SC filter from low to high order. Figures 2, 3, 4, 5 and 6 show the performance of transient and frequency responses for LC, RC and SC networks. The summary from graph is listed below.

- (a) Transient response of SC filter is faster than LC and RC networks.
- (b) Peak, settling and duplicating time for SC are lower than LC and RC networks.
- (c) Peak overshoot voltage for SC is also less than the LC and RC networks.
- (d) SC has less oscillation and stable.

The transient response produced by MFB technique is better than Leapfrog and FDNR. The performance sequences of transient response for SC design are MFB, Leapfrog followed by FDNR. Transient responses produced by Leapfrog and FDNR are very close to each other. Further investigation reveals that the Leapfrog performance is better than FDNR. This is illustrated in Figure 5.

Table 4: Distribution for Device, Total Capacitance and Frequency Sampling for Various Switched-Capacitor.

Tech-nique	Order	Frequency Sampling (khz)	No. Op-Amp	No. Sw	No. Cap	Total Capacitance (F)
MFB	5	100	3	32	13	3.967E-12
	10	200	5	60	25	6.836E-12
	15	400	8	92	38	1.002E-11
LEAP-FROG	5	100	5	24	12	1.729E-11
	10	200	10	44	22	5.269E-11
	15	400	15	64	32	1.390E-10
FDNR	5	100	4	36	14	1.677E-07
	10	200	10	80	32	2.915E-07
	15	400	14	116	45	3.917E-07

(a)

(b)

(c)

Figure 1: (a) Network for MFB Switched-Capacitor Design (b) Network for Leapfrog Switched-Capacitor Design (c) Network for FDNR Switched-Capacitor Design.

Figure 6 shows that the frequency response of SC is closer to the ideal response except for the Leapfrog design. This effect will contribute little noise and distortion. The slope sequences for the frequency response of various SC techniques are MFB, FDNr and Leapfrog. The distribution of cutoff frequency and error for the above design are tabulated in Table V. The simulation shows that the excellent average of cutoff frequency is 9974 Hz with errors of 0.26%. These values are very close to the calculation and small percentage errors from the MFB approached.

Table 4 also shows that the MFB SC design contributes low total capacitance as compared with other techniques. Therefore, the stray capacitance which probably occurred in this MFB type of SC is low.

Figure 2: Transient Response for MFB Design (a) 5th-order (b) 10th-order (c) 15th-order.

Figure 3: Transient Response for LEAPFROG Design (a) 5th-order (b) 10th-order (c) 15th-order.

Figure 4: Transient Response for FDNR Design (a) 5th-order (b) 10th-order (c) 15th-order.

Figure 5: Comparisons of Transient Response for Various Switched Capacitor Design (a) 5th-order (b) 10th-order (c) 15th-order.

Table 5: Frequency Cutoff for Various Switched-Capacitor Design.

Technique	Order	Calculation (Hz)	Simulation (Hz)	Average (Hz)	Error (%)
MFB	5	10000	9971	9974	0.26
	10		9980		
	15		9971		
LEAP-FROG	5	10000	9431	9640	3.60
	10		9556		
	15		9934		
FDNR	5	10000	9906	9952	0.48
	10		9974		
	15		9977

(a)

(b)

(c)

Figure 6: Comparisons of Transient Response for Various Switched Capacitor Design (a) 5th-order (b) 10th-order (c) 15th-order.

6. CONCLUSION

The MFB, Leapfrog and FDNR techniques have been discussed for the realization of SC filter design based on the LC network. The MFB approach is found to be very significant in increasing and improving transient, frequency response and total capacitance. In addition to that the size of integrated circuit produced is relatively small.

7. REFERENCES

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