

Biquadratic SC Filters with Small GB Effects

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Observe that Switched-Capacitor systems (filters) have n different topologies being n the number of clock phases. Typically $n=2$ for many practical cases. However these two topologies can have quite different design constrains on the Op Amp specifications. This material is focus on studying how to determine the GB specifications for a certain clock frequency and capacitive feedback.

Furthermore we will learn that an optimal sequence of clock phases is vital for a good SC frequency and time responses.



How the Op Amp GB affects the Switched Capacitor Filter performance?

- The Op Amp behavior is of a continuous system nature independent if the system(filter) is continuous or discrete time.
- A rule of thumb in CT circuits is to operate at about $1/10$ of the maximum available BW of the closed loop gain
- We will discuss how to determine the minimum GB in a switched capacitor filter as a function of clock frequency and the capacitive feedback network.

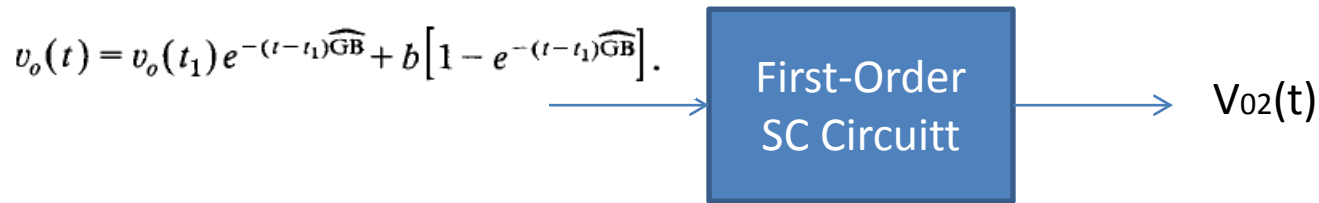
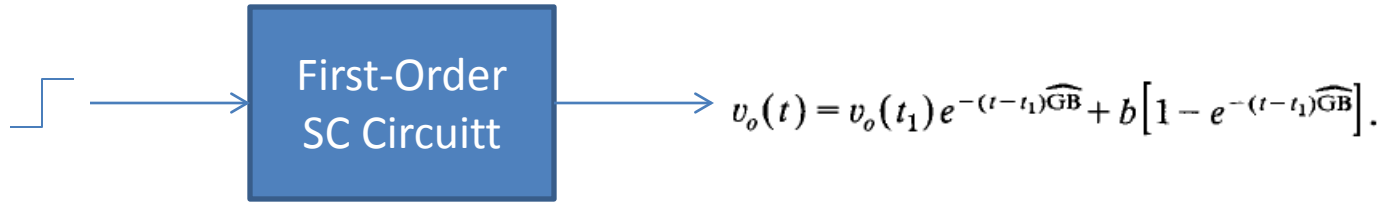
Capacitive Feedback Coefficient “ a ”

For the common case where the noninverting terminal of the op amp is grounded and the circuit contains no nodes other than those connected directly to an input or a terminal of the op amp it can be shown that the value of a for each clock phase is obtained from the expression

$$a = \frac{\sum C_f}{\sum C_i} \quad (2)$$

where the C_f sum is over all feedback capacitors (connected directly between the op amp output and the inverting input terminal) and the C_i sum is over all capacitors connected to the negative terminal of the op amp. Note that a is bounded between 0 and 1.

Time response of Switched-Capacitor Filters



Where

$$v_{02}(t) = \frac{h\widehat{GB}_2}{\widehat{GB}_2 - \widehat{GB}_1} e^{-\widehat{GB}_1(t-t_1)}(v_{01}(t_1) - b_1) + e^{-\widehat{GB}_2(t-t_1)} \cdot \left[v_{02}(t_1) - \frac{\widehat{GB}_2 h}{\widehat{GB}_2 - \widehat{GB}_1} (v_{01}(t_1) - b_1) - hb_1 - b_2 \right] + hb_1 + b_2 \quad (9)$$

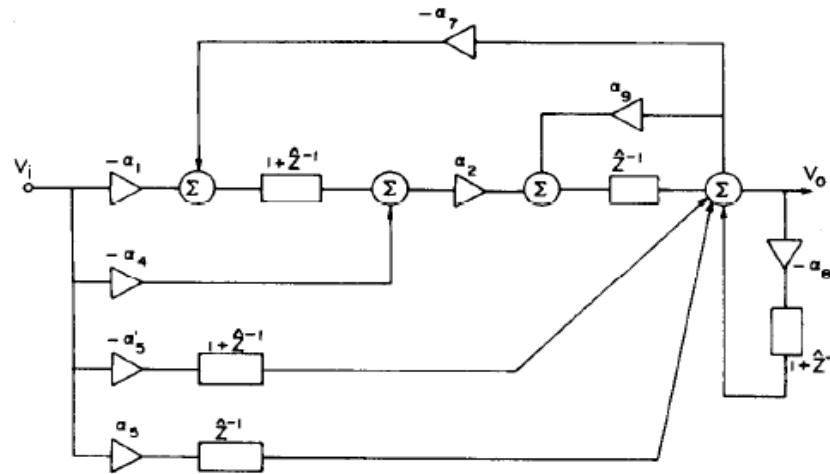
$$\text{where } \widehat{GB}_2 = a_{22}GB_2.$$

Observe that a step input is preferable than an exponential input

Biquad 1

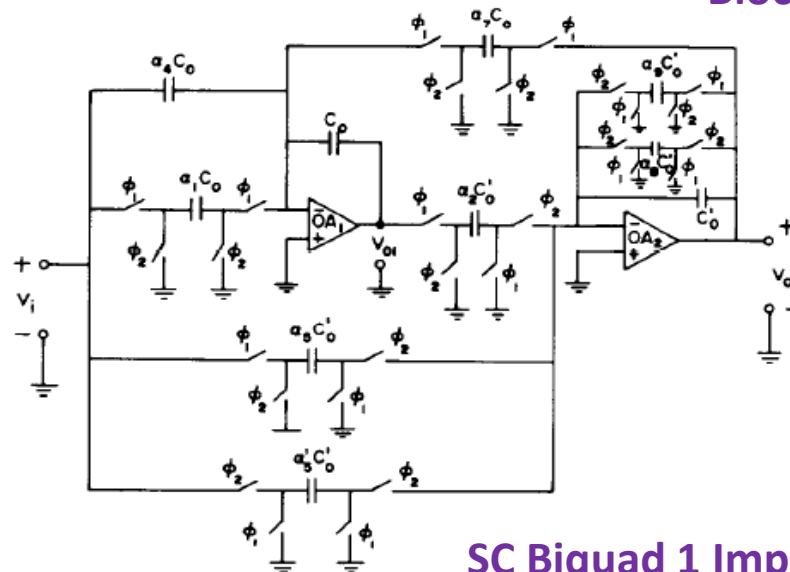
Switched Capacitor Filter

Reader.- Draw the equivalent Circuits for each clock phase.
How much capacitance is present at the negative Op Amp terminals for both clock phases?



(a)

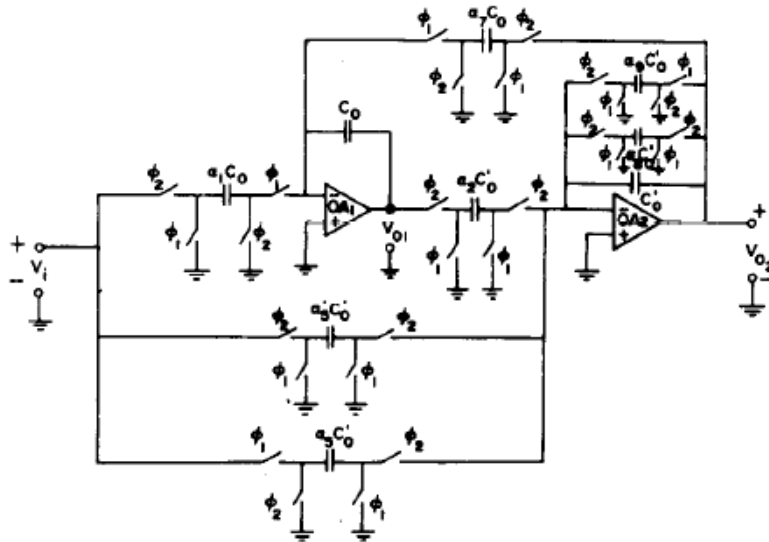
Block Diagram



(b)

SC Biquad 1 Implementation

Fig. 2. Generation of Biquad 1. a) Flow diagram. b) SC implementation.



$$a_{lm} = \frac{\sum C_{fi} + \sum C_{fn}}{\sum C_{ii} - \sum C_{ni}}$$

TABLE II
EFFECTIVE GB MATRICES FOR BIQUADS 1 AND 2

PHASE	BIQUAD 1	BIQUAD 2
ϕ_1	$\begin{bmatrix} \frac{1}{1+\alpha_1+\alpha_4+\alpha_7} & 0 \\ \frac{\alpha_7}{1+\alpha_1+\alpha_4+\alpha_7} & 1 \end{bmatrix}$	$\begin{bmatrix} \frac{1}{1+\alpha_1+\alpha_7} & 0 \\ 0 & 1 \end{bmatrix}$
ϕ_2	$\begin{bmatrix} \frac{1}{1+\alpha_4} & 0 \\ 0 & \frac{1+\alpha_8}{1+\alpha_2+\alpha_5+\alpha_5'+\alpha_8+\alpha_9} \end{bmatrix}$	$\begin{bmatrix} 1 & \frac{\alpha_2}{1+\alpha_8+\alpha_9+\alpha_2+\alpha_5+\alpha_5'} \\ 0 & \frac{1+\alpha_8}{1+\alpha_2+\alpha_5+\alpha_5'+\alpha_8+\alpha_9} \end{bmatrix}$

TABLE IV
NUMERICAL VALUES OF THE EFFECTIVE GB MATRICES FOR BIQUADS 1 AND 2 CONSIDERED IN THE EXAMPLE

PHASE	BIQUAD 1	BIQUAD 2
ϕ_1	$\begin{bmatrix} 0.456 & 0 \\ 0.544 & 1 \end{bmatrix}$	$\begin{bmatrix} 0.456 & 0 \\ 0 & 1 \end{bmatrix}$
ϕ_2	$\begin{bmatrix} 1 & 0 \\ 0 & 0.426 \end{bmatrix}$	$\begin{bmatrix} 1 & 0.491 \\ 0 & 0.426 \end{bmatrix}$

Let us investigate the effective GB for different topologies and clock phases

TABLE II
EFFECTIVE GB MATRICES FOR BIQUADS 1 AND 2

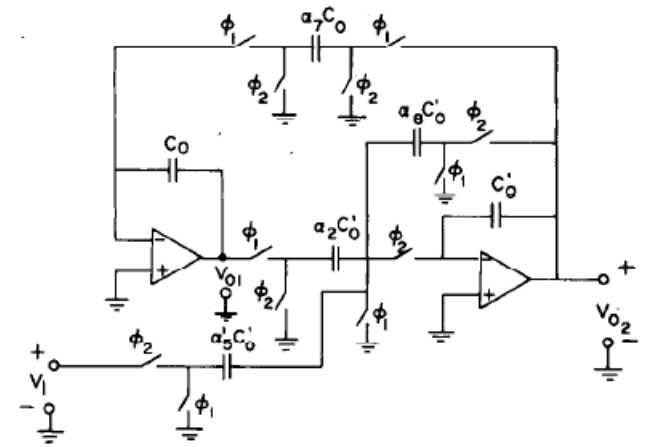
PHASE	BIQUAD 1	BIQUAD 2
ϕ_1	$\begin{bmatrix} \frac{1}{1+\alpha_1+\alpha_4+\alpha_7} & 0 \\ \frac{\alpha_7}{1+\alpha_1+\alpha_4+\alpha_7} & 1 \end{bmatrix}$	$\begin{bmatrix} \frac{1}{1+\alpha_1+\alpha_7} & 0 \\ 0 & 1 \end{bmatrix}$
ϕ_2	$\begin{bmatrix} \frac{1}{1+\alpha_4} & 0 \\ 0 & \frac{1+\alpha_8}{1+\alpha_2+\alpha_5+\alpha_5'+\alpha_8+\alpha_9} \end{bmatrix}$	$\begin{bmatrix} 1 & \frac{\alpha_2}{1+\alpha_8+\alpha_9+\alpha_2+\alpha_5+\alpha_5'} \\ 0 & \frac{1+\alpha_8}{1+\alpha_2+\alpha_5+\alpha_5'+\alpha_8+\alpha_9} \end{bmatrix}$

$$H^{ee}(z) = \frac{V_{o2}^e(z)}{V_i^e(z)} = - \frac{\alpha'_5}{1 + \alpha_8} \frac{z^2 - z[\alpha_5 + \alpha'_5 - \alpha_2(\alpha_1 + \alpha_4)]/\alpha'_5 + [\alpha_5 - \alpha_2\alpha_4]/\alpha'_5}{z^2 - z[2 + \alpha_8 + \alpha_9 - \alpha_2\alpha_7]/(1 + \alpha_8) + (1 + \alpha_9)/(1 + \alpha_8)}$$

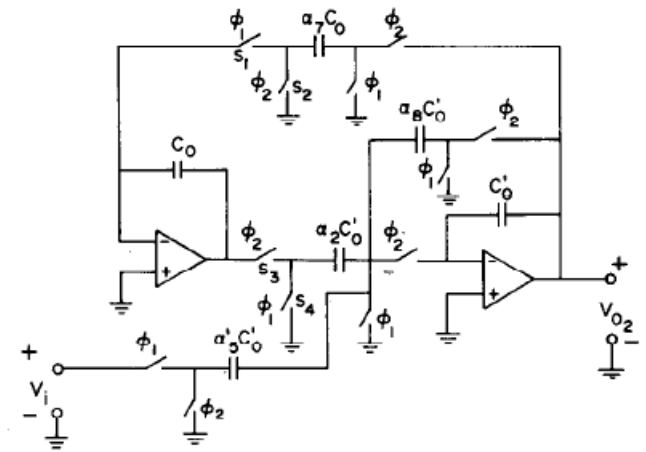
IDEAL TRANSFER FUNCTIONS

The ideal transfer function of the Biquad 2 is given by

$$H^{ee}(z) = \frac{V_{o2}^e(z)}{V_i^e(z)} = - \frac{\alpha'_5}{1 + \alpha_8} \cdot \frac{z^2 - z(\alpha'_5 + \alpha_5 - \alpha_1\alpha_2)/\alpha'_5 + \alpha_5/\alpha'_5}{z^2 - z \frac{2 + \alpha_8 + \alpha_9 - \alpha_2\alpha_7}{1 + \alpha_8} + \frac{1 + \alpha_9}{1 + \alpha_8}}$$



(a)



(b)

Fig. 4. SC Bandpass minimum switch configurations. (a) Biquad 1. (b) Biquad 2.

Example of BP SC Filter

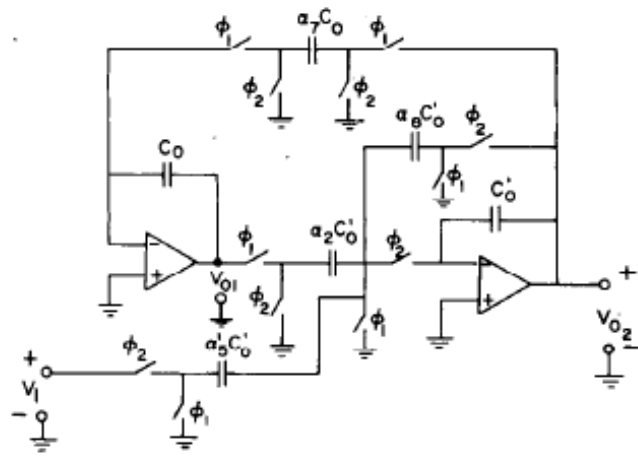
Q=16, fo=1.633KHz and fs= 8KHz

For comparative purposes the design specifications are the same as used by Fleischer and Laker [5]; specifically, a bandpass structure with center frequency/sampling frequency equals 1.633 kHz/8 kHz, a quality factor of $Q=16$ and a peak gain of 10 dB at the center frequency. The resulting transfer function of the type² BPOO [5] is given by

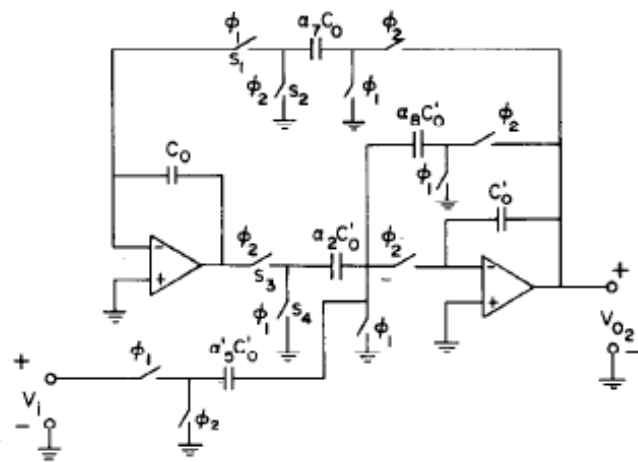
$$H^{ee}(z) = \frac{0.1953(z-1)z}{z^2 - 0.5455z + 0.9229}$$

TABLE III
BANDPASS REALIZATION WITH $\alpha_0 = 0$

Capacitor	Initial Design	Dynamic range Adjusted	Final Design
C_0	1.0	1.249	1.0
C'_0	1.0	1.0	11.970
$\alpha_2 C'_0$	1.0	1.249	14.953
$\alpha'_5 C'_0$	0.212	0.212	2.533
$\alpha_7 C_0$	1.492	1.493	1.195
$\alpha_8 C'_0$	0.084	0.084	1.0
C_T	(Total capacitance in terms of unit capacitance, C_u)		32.651



(a)



(b)

Fig. 4. SC Bandpass minimum switch configurations. (a) Biquad 1. (b) Biquad 2.

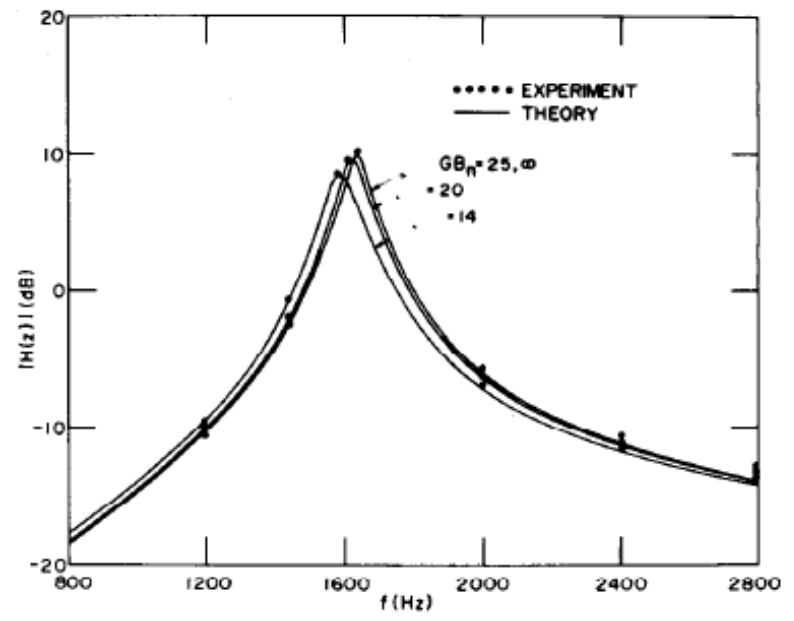


Fig. 5. Theoretical and experimental frequency response of Biquad 1.

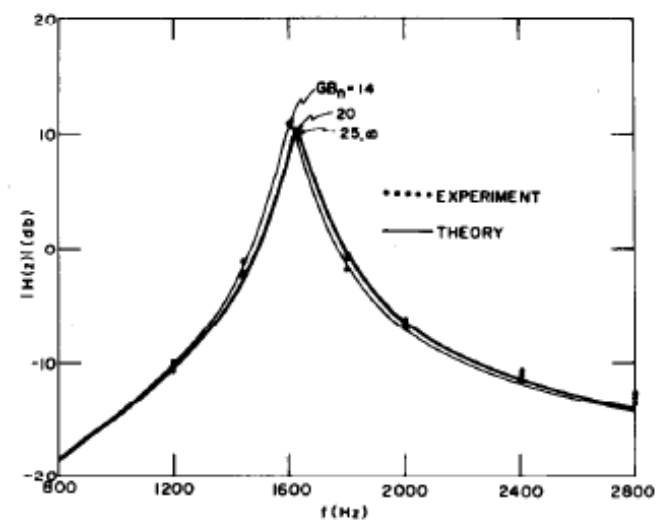


Fig. 6. Theoretical and experimental frequency response of Biquad 2.

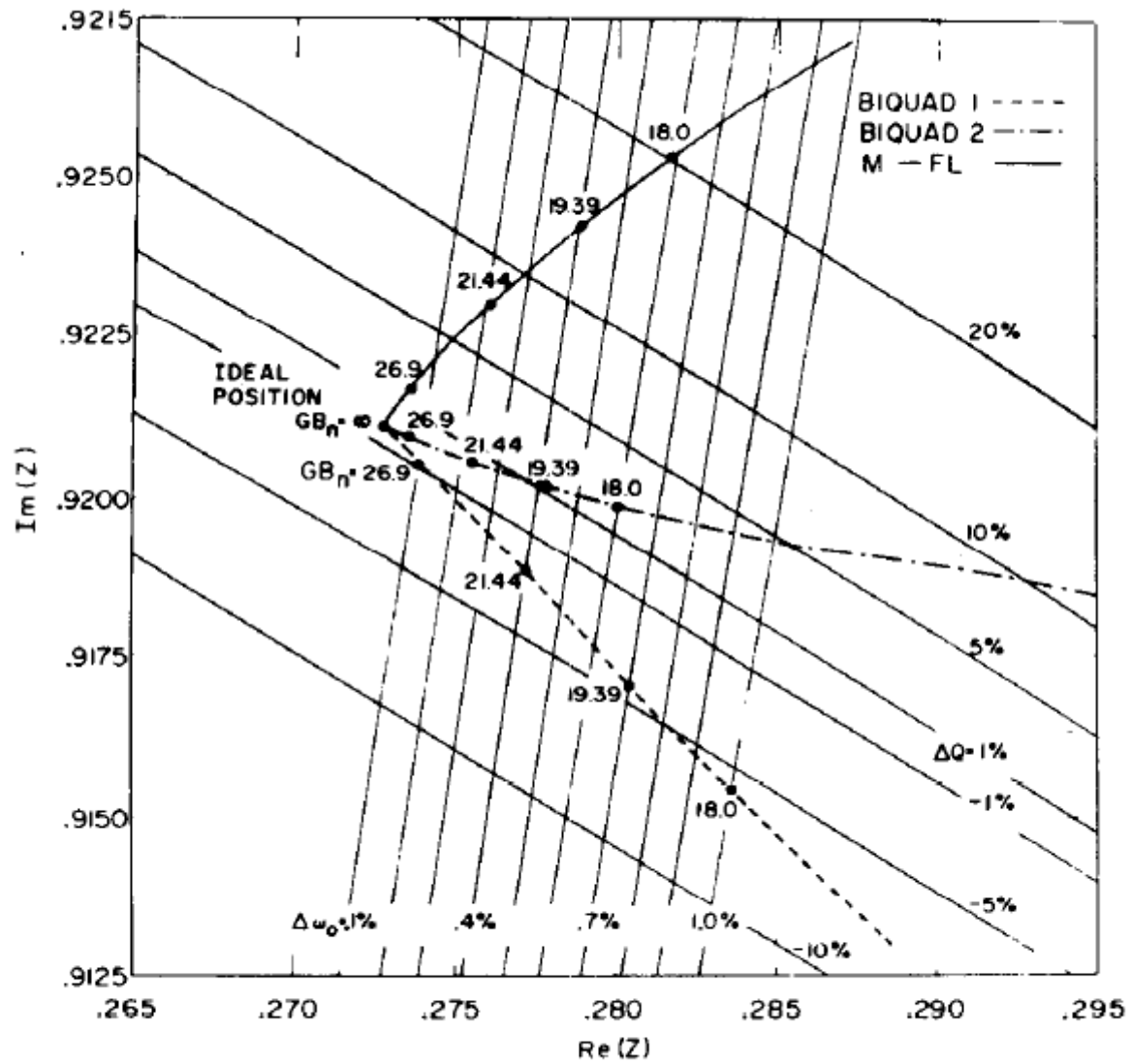


Fig. 7. Root locus of Biquad 1, 2, and M-FL for the case of identical GB's.



Conclusions

General design guidelines to select appropriate switching phasing in obtaining low GB dependence SC filter have been presented. The SC effective GB matrices, which can generally be obtained by inspection, have been shown to be useful in predicting GB effects. Two general biquadratic SC topologies with reduced GB effects have been reported. These circuits were shown to have favorable passive sensitivities and total capacitances. The theoretical and experimental results are in good agreement.

The analysis for both biquads allows the designer to predict the ω_0 and Q deviations due to the GB's of the op amps.

$$aGBT > 5$$