CMOS - y(s) Filters

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abstract:

The concept of active - y(s) filters is introduced and illustrated through the CMOS - y(s) biquad. This allows synthesis taking account equal dissipation of the y(s) components with the dynamics of the system resulting from the, possibly non-zero, pole of the amplifier. This allows CMOS filters to be constructed with equally dissipative capacitors as the only passive components, as illustrated by an experimental example.

I. Introduction:

Switched capacitor filters [1] have recently become popular because of their suitability for realization in integrated circuit form for accurate designs depending primarily upon the ratios of small temperature insensitive MOS capacitors which can be matched accurately [2]. The intuitive concept is that by switching charge on and off of a capacitor it can effectively act as a resistor at least for signal frequencies significantly below the switching frequency [3]. Practically these are known to work well [4, p. 1042], as our experience confirms, and thus exact analyses [5], specific practical configurations [6], and general design techniques [4] have been developed. On top of this one has cautions on the resistor/switched-capacitor correspondence [7] to which we would add our word that the incorporation of better and better switches will lead to capacitor currents closer and closer to impulses thus subjecting components to burnout.

To get around the problems associated with switching capacitors, such as sampling frequency limitations, switching transient noise and component burnout, there now exists a theory of active filters using amplifiers and ratios of capacitors due to Schaumann [8]–[10]. Here we show that this can be extended to allow even higher frequency designs using our previous results for active-R circuits [11] as well as extended to the use of general circuits in place of the capacitors. Especially this should be important for incorporating the loss of capacitors in active-C filters.

II. CMOS – $y(s)$ Circuits

Our results are based upon the observation that the coefficients obtained in the transfer functions of active-C, or active-R, filters depend only on the ratios of capacitors, or resistors, in the realization. Thus any set of components could replace the capacitors as long as the ratio of admittances of all pairs of the replacing components are a real constant. In other words if y_i is the admittance of the ith component then

$$y_i(s) = a_i \cdot y_o(s), \quad a_i = \text{real number}. \tag{1}$$

For instance consider the "biquad" circuit of Fig. 1 where the voltage amplifiers are taken to have zero input current and voltage gains $A_i(s)$. Direct analysis gives

$$\frac{v_o}{v_i}(A_1, A_2) = \frac{-(y_1/y_3)A_1A_2}{A_1A_2 + (y_2/y_3)A_1 - [(y_1+y_2+y_3)/y_3]} \tag{2a}$$

$$\frac{v_1}{v_i} = \frac{1}{A_1}\frac{v_2}{v_i} = \frac{1}{A_1A_2}\frac{v_o}{v_i} \tag{2b}$$

Clearly, only the ratios of admittances are of importance to this biquad circuit. Therefore, if (1) holds the frequency dependence of the transfer functions of (2) results through the frequency dependence of the amplifiers

In the realization of our biquad through CMOS devices the two amplifiers of Fig. 2 are of interest. These amplifiers have the respective gains

$$\frac{v_x}{v_w} = A_a(s) = -\frac{GB_a}{s+\sigma_0} \quad (3a)$$

$$\frac{v_z}{v_y} = A_b(s) = +\frac{GB_b}{s+\sigma_0} \quad ; \quad GB_b = G_0 \cdot GB_a \quad (3b)$$

where GB is the gain bandwidth and σ_0 is the 3db frequency. Both GB_a and σ_0 are dependent upon the bias voltages $V_p \approx V_n$ while $V_{pp} \approx V_{nn}$ is chosen such that G_0 independent of s over the frequency range of interest ($V_{pp} >> V_p$).

We will treat simultaneously the situations where A_2 is either a positive or negative gain amplifier while A_1 is of negative gain. Then substituting $A_1 = -GB_1/(s+\sigma_0)$ and $A_2 = \pm GB_2/(s+\sigma_0)$ into (2a) using (1) and rearranging gives

$$T(s) = \frac{v_o}{v_i}(s) = \frac{\mp GB_1 \cdot GB_2\, c_1}{s^2 + (2\sigma_0 + GB_1 c_2)s + (\sigma_0^2 + GB_1 c_2 \sigma_0 \pm GB_1 \cdot GB_2 c_3)} \quad (4a)$$

where

$$c_i = a_i/[a_1+a_2+a_3] \quad (4b)$$

The upper signs here and below go with opposite signed amplifiers while the lower signs are for identical, negative gain, amplifiers.

To this point we see that the biquad circuit of Fig. 1 can realize any transfer function of the form of $T(s)$ when constructed with CMOS amplifiers and components all of whose ratios of admittances are constant. The frequency dependence of $T(s)$ results solely from the CMOS-pair's "internal pole," as reflected in (3) while convenient components, such as lossy capacitors which are equally dissipative, can be used. In short, the non-idealness of the CMOS amplifiers can be used to obtain the system dynamics whereas nonidealness of the passive components can be cancelled through the use of equally dissipative elements, giving designs which are built upon the very nonidealness of the circuit elements.

There are, however, some realizability constraints, which in this particular case of the biquad are rather interesting. If we set the denominator of $T(s)$ of (4a) equal to the universal degree two polynomial $D(s) = s^2 + (\omega_0/Q)s + \omega_0^2$ we directly find

$$r_2 = [(\omega_0/Q) - 2\sigma_0]/GB_1 \qquad (5a)$$

$$r_3 = \pm[(\sigma_0^2 + \omega_0^2) - \sigma_0(\omega_0/Q)]/GB_1 \cdot GB_2 \qquad (5b)$$

Now from (4b) the constraint of passive realizability on the y_i requires $0 \le r_i < 1$ which in terms of (5) means

$$2\sigma_0 \le (\omega_0/Q) < GB_1 + 2\sigma_0 \tag{6a}$$

$$\mp(\sigma_0^2+\omega_0^2) \le \mp\sigma_0(\omega_0/Q) < GB_1\cdot GB_2 \mp (\sigma_0^2+\omega_0^2) \tag{6b}$$

When $\sigma_0 \neq 0$ it can be divided through (6b) and we obtain the following constraints placed directly upon Q for realizability of our two types of biquads.

Negative & Positive Gain amplifiers ($GB_1 = GB = GB_2/G_0$):

$$\max\left\{\begin{array}{c}\dfrac{(\omega_0/2\sigma_0)}{1+(GB/2\sigma_0)}\\[2ex] \dfrac{(\omega_0/\sigma_0)}{1+(\omega_0/\sigma_0)^2}\end{array}\right\} < Q < \min\left\{\begin{array}{c}(\omega_0/2\sigma_0)\\[2ex] \dfrac{(\omega_0/\sigma_0)}{1+(\omega_0/\sigma_0)^2 - G_0(GB/\sigma_0)^2}\end{array}\right. \tag{7a}$$

Both Negative Gain amplifiers ($GB_1 = GB_2 = GB$):

$$\max\left\{\begin{array}{c}\dfrac{(\omega_0/2\sigma_0)}{1+(GB/2\sigma_0)}\\[2ex] \dfrac{(\omega_0/\sigma_0)}{1+(\omega_0/\sigma_0)^2+(GB/\sigma_0)^2}\end{array}\right\} < Q \le \min\left\{\begin{array}{c}(\omega_0/2\sigma_0)\\[2ex] \dfrac{(\omega_0/\sigma_0)}{1+(\omega_0/\sigma_0)^2} \le \dfrac{1}{2}\end{array}\right. \tag{7b}$$

It should be observed that with perfect integrators, where $\sigma_0 = 0$, the use of two negative gain amplifiers does not lead to a (stable) realizable situation, as seen by (6b) where $\omega_0^2 \le 0$ becomes required. Since the assumption of $\sigma_0 = 0$ is most frequently made in the literature [9], [11], [12] one can see why only the circuit containing oppositely signed amplifiers has occurred. But simplicity of the negative gain amplifiers (two less transistors) makes the case of identical amplifiers worthwhile considering when the rather severe Q constraint of (7b) can be satisfied.

IV. Discussion

We have directly shown that CMOS - $y(s)$ biquads can be designed taking into account the CMOS internal pole to obtain the dynamics (dependence upon s) and using proportional, but otherwise arbitrary, components to set the constants of the transfer function. Clearly the result extends to other configurations, to arbitrary degree, and to any amplifier with voltage transfer function $\pm GB/(s+\sigma_0)$ (drawing zero input current and having negligable output impedance). Thus, the results are valid for op-amp - $y(s)$ filters.

The effects of the amplifiers being nonperfect integrators, that is $\sigma_0 \neq 0$, are seen through the limitations placed upon realizable Q. As seen by (7) these effects can be rather restrictive and hence it is worthwhile evaluating other configurations to see if larger ranges of Q can be obtained.

Reference [14] covers many practical details of active - R type filters. The discussion there is pertinent to active - $y(s)$ filters and is worthwhile the attention of anyone interested in these circuits.

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Figure Titles

1. Basic Biquad Structure

2. CMOS Voltage Amplifiers

   a) Negative Gain

   b) Positive Gain

      $V_{pp} >> V_p$

      $V_{mm} >> V_m$

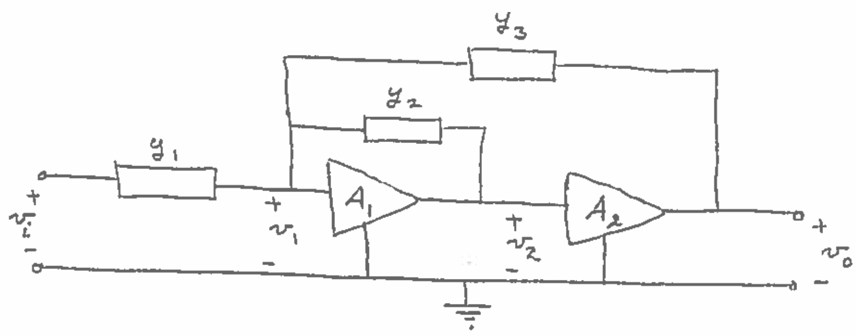
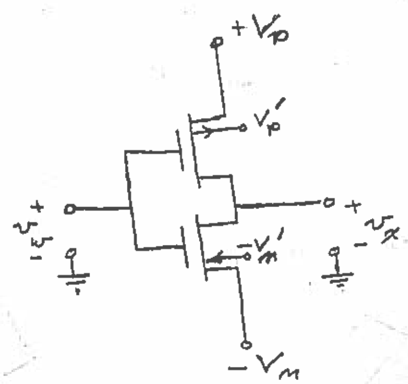
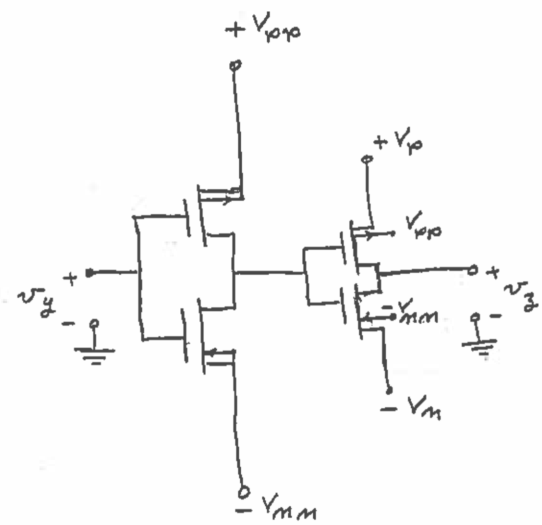


Figure 1



a)



b)

Figure 2