Express Letters

Current-Mode Multiple-Feedback Filters

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Abstract—**Current-mode multiple-feedback filters, containing the same elements as their Voltage-mode counterparts, are proposed in this paper. Both classes of circuits are analyzed and compared in terms of bandwidth. Experimental results supporting the theoretical analysis are given.**

I. Introduction

In [1] the adjoint transformation is suggested as a straightforward method to obtain current-mode circuits from their voltage-mode counterparts. This transformation is applied in [2] to a class of op-amp based biquadratic filters, known as positive-feedback circuits. The class of negative-feedback biquad (NFB) is eluded in this latter paper because in this type of filters a stable finite gain voltage amplifier cannot be isolated. To cope with the transformation of these NFB's we have proposed and practically demonstrated an alternative procedure [3].

In both cases, the current-mode filters resulting from the transformation no longer contain the op-amp as the active device. They use current amplifiers made up of current conveyors, buffers or op-amps with current sensing. This fact makes it difficult to compare in a straightforward manner the current and voltage versions of a given biquadratic filter, although experimental results reported by some authors seem to demonstrate that the current-mode circuits exploit all of the available bandwidth of the active devices. This suggest that current-mode circuits should be capable of achieving higher operating frequencies than the corresponding voltage-mode counterparts.

In this paper a different class of op-amp based biquadratic filters, the infinite-gain multiple-feedback filters, is transformed into its current version. This class has so far eluded any such transformation because the op-amp is configured without resistive feedback loop. The current-mode multiple-feedback filters contain also a single op-amp as the active element, and therefore an absolute comparison between voltage and current versions is feasible. In this paper we demonstrate, both theoretically and practically, that the current-mode multiple-feedback filters can extend the useful bandwidth with respect to their classical voltage-mode counterparts up to nearly the GB product of the op-amp.

This result is particularly interesting because voltage- and current-mode multiple-feedback filters contain exactly the same active and passive components.

However, to appreciate the difference between the current and voltage filters, they have to be designed to minimize the effect of op-amp parasitic impedances. If not, such parasitic elements play a dominant role in the high frequency behavior, and the advantages of the current-mode filter cannot be realized.

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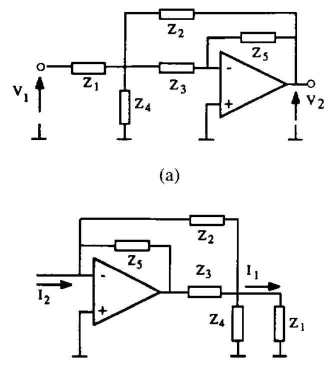

Fig. 1.

II. The Current-Mode Infinite-Gain Multiple-Feedback Filter

Fig. 1(a) shows the general scheme of an infinite-gain multiple-feedback filter in its classical voltage-mode version [4]. By properly choosing the passive components, low-, band-, and high-pass characteristics can be achieved. In these topologies the op-amp is working as an infinite-gain voltage amplifier.

To obtain the corresponding current version we can apply the adjoint transformation in the usual way [1]. The resulting circuit is straightforward by only taking into account that the single-input single-output infinite-gain current amplifier required can be realized directly by means of one op-amp with the noninverting input terminal grounded. The nullator-norator concept can be also invoked to perform the transformation [5]–[7], considering that in our original circuit the op-amp is equivalent to a nullator plus a norator, both grounded, and then the transformation has the effect of interchanging them.

Both approaches are equivalent, and the resulting circuit is therefore the same, as shown in Fig. 1(b), with the current directions as indicated in this figure.

Therefore, the transfer function of the two circuits in Fig. 1 is as follows [4]:

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{-Y_1Y_3}{(Y_1+Y_2+Y_3+Y_4)Y_5+Y_2Y_3}. \tag{1}$$

III. Frequency-Response Analysis

As we said above, the circuits at hand are very useful in illustrating how much is gained with the current-mode approach, because the two circuits in Fig. 1 contain exactly the same passive and active components.

Assuming a limited frequency response for the op-amp, modeled by a single pole, the transfer function of the system in Fig. 1(a) can be written as

$$\frac{V_2}{V_1} = \frac{-Y_1Y_3}{(Y_1+Y_2+Y_3+Y_4)\left[Y_5+\frac{s}{\mathrm{GB}}(Y_3+Y_5)\right]-Y_3^2\frac{s}{\mathrm{GB}}+Y_2Y_3} \tag{2}$$

where GB is the gain-bandwidth product of the op-amp.

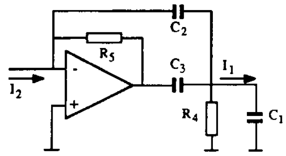

Fig. 2.

The current-mode circuit in Fig. 1(b) has the following transfer function:

$$\frac{I_1}{I_2} = \frac{-Y_1Y_3\left[1 - \frac{Y_2}{Y_3}\frac{s}{\mathrm{GB}}\right]}{(Y_1 + Y_2 + Y_3 + Y_4)\left[Y_5 + \frac{s}{\mathrm{GB}}(Y_2 + Y_5)\right] - Y_2^2\frac{s}{\mathrm{GB}} + Y_2Y_3}. \tag{3}$$

From the expressions above it is apparent that the initial equivalence no longer holds. Whereas the form of the denominator, and thus of the poles, is similar for both transfer functions (note that Y_2 and Y_3 must be in any case both capacitors or resistors), the current transfer function presents an additional zero in the right half plane. This zero can be used to compensate the parasitic pole introduced by the op-amp. To see how this can be done, we can write expression (3) in a more convenient way:

$$\frac{I_1}{I_2} = \frac{-Y_1Y_3\left[1 - \frac{Y_2}{Y_3}\frac{s}{\mathrm{GB}}\right]}{[(Y_1 + Y_2 + Y_3 + Y_4)Y_5 + Y_2Y_3]\left[\frac{s}{\mathrm{GB}} + 1\right] + \frac{s}{\mathrm{GB}}Y_2(Y_1 + Y_4)}. \tag{4}$$

If the term in the denominator:

$$\frac{s}{\mathrm{GB}}Y_2(Y_1 + Y_4) \tag{5}$$

could be considered negligible, which as we will see is a reasonable assumption, then the current transfer function can be approximated by

$$\frac{I_1}{I_2} \cong \frac{-Y_1Y_3\left[1 - \frac{Y_2}{Y_3}\frac{s}{\mathrm{GB}}\right]}{[(Y_1 + Y_2 + Y_3 + Y_4)Y_5 + Y_2Y_3]\left[\frac{s}{\mathrm{GB}} + 1\right]}. \tag{6}$$

Then, if we impose the condition

$$Y_2 = Y_3 \tag{7}$$

the modulus of the parasitic pole and zero are equal, which indicates that, as far as the magnitude response is concerned, a pole-zero compensation occurs. The price to be paid for this improvement in magnitude response is a worsening in phase performance.

IV. Example and Experimental Results

Let us consider the high-pass multiple-feedback filter whose current-mode version is indicated in Fig. 2. Its current transfer function can be easily obtained from expression (4), where the decomposition suggested is apparent:

$$\frac{I_1}{I_2} = \frac{-\frac{C_1}{C_3}s^2\left[1 - \frac{C_2}{C_3}\frac{s}{\mathrm{GB}}\right]}{\left[s^2 + \frac{s}{R_5}\frac{C_1+C_2+C_3}{C_2C_3} + \frac{1}{R_4R_5C_2C_3}\right]\left[\frac{s}{\mathrm{GB}} + 1\right] + \frac{s^3}{\mathrm{GB}}\frac{C_1}{C_3} + \frac{s^2}{\mathrm{GB}C_3R_4}} \tag{8}$$

To consider negligible the two last terms in the denominator with respect to the remaining terms of the same order, the following inequalities should be fulfilled:

$$\frac{1}{C_3R_4} \ll \mathrm{GB} + \frac{1}{R_5C_2}\left[1 + \frac{C_1 + C_2}{C_3}\right] \tag{9}$$

$$\frac{C_1}{C_3} \ll 1. \tag{10}$$

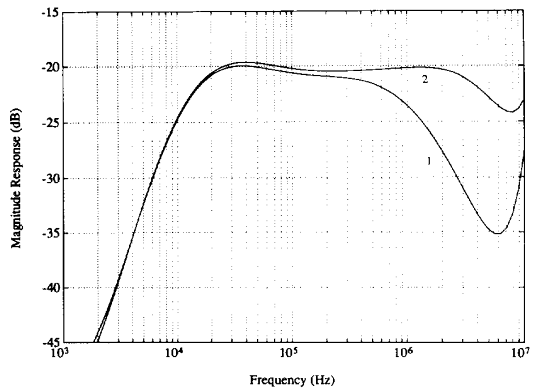

Fig. 3.

Condition (9) is easily fulfilled for instance if the characteristic frequencies are far enough from GB. If not, the system should be designed so that $R_4 \gg R_5$.

The second condition only depends on a capacitor ratio, C_1/C_3, that has to be made as low as possible. It has to be noted that this ratio is exactly the ideal high frequency gain of the filter.

To demonstrate this design approach practically, we breadboarded and measured two prototypes, current and voltage versions of the same filter. The component values used were as follows: $C_1 = 10$ pF, $C_2 = C_3 = 100$ pF, $R_4 = 100$ KΩ, $R_5 = 220$ KΩ, op-amp = 741 (GB = 1.2 MHz). They ideally provide a Butterworth response with cutoff frequency of 10.73 KHz and a 20-dB attenuation at high frequencies. To obtain the frequency response of the current-mode multiple-feedback filter two additional voltage-to-current and current-to-voltage stages were used, both them built with an AD844 transimpedance op-amp and a 5.6-KΩ resistor.

In Fig. 3 we show the magnitude response of the two filters. Plots 1 and 2 correspond to the voltage and current transfer function, respectively. The parasitic pole located close to GB is apparent in the first curve, whereas in the second it is compensated producing a flatter response at high frequencies.

Passive components were chosen so as to minimize the influence of the op-amp output impedance. If not, such impedance creates another parasitic pole below GB (in both voltage and current filters!) that invalidates our analysis and therefore the potential advantages of the current-mode filter.

In our simulations and measurements we observed that for low resistance and/or high capacitance values (impedances comparable to that of the op-amp output), the responses of both filter versions are quite similar, and no advantage can be claimed in favor of either one or the other.

This result should, at least, warn against the absolute affirmation that current versions of voltage filters offer wider bandwidths. In many cases, and we have shown a very illustrative one, that improvement is possible but it is also true that other second-order effects can spoil this potential advantage.

Many efforts are being made, through current-mode techniques, to extend the op-amp use to frequencies up to GB. These attempts will have limited success unless the effect of parasitic op-amp impedances, that play a dominant role at high frequencies, are taken into account. The circuits considered in this paper are demonstrative of this fact.

V. Conclusions

Current and voltage-mode versions of the popular infinite-gain multiple-feedback filters have been analyzed, compared and experimentally tested. These filters are very interesting from the point of view of allowing a direct comparison between current and voltage domains because both versions contain exactly the same passive and active components.

When considering the limited frequency response of the op-amps used, the current-mode version offers some potential improvements in bandwidth owing to a pole-zero cancellation. However, to obtain full advantage of this property, filters should be designed to minimize the influence of parasitic impedances.

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