Study of Practical Problems in Two-Loop CCTA Based Biquad: Finite Attenuations in Stop Bands

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Abstract

Quite neglected and underlying problem of modern active functional blocks is presented and demonstrated in this contribution on a current-mode active filter. The discussed problem is an undesirable transfer in stop band of multifunctional frequency filters. It is caused by several occasions related to small-signal parameters of active elements (impedance levels) in the circuit. In some cases it leads to parasitic feedback and undesirable transfers in circuit. Problems are discussed on example with KHN-type filter where quite novel active element known as Current Conveyor Transconductance Amplifier (CCTA) is used.

1. Introduction

The construction and design of circuits in current-mode (CM) [1] is quite popular in recent years. However, there are some hidden disadvantages and problems caused by circuit structure and real features of used active elements that can damage running of transfer function. These problems and their reasons are not so clear from many of recently published works focused on novel applications. The authors usually describe not so important current/voltage tracking or amplification errors in many cases of active filters [2-3] but mentioned problems with transfer functions are not so significant in comparison to considerable problems with finite attenuation in stop band of some transfer functions, which are typical for loop and multi-loop integrator based filters [4]. This problem is not so clear and not always observable when authors (for example [5-6]) use linear axis in graph of transfer function, instead of logarithmic (dB). This work is not focused on noise, dynamic range and total harmonic distortion analyses because of limited space and because it is not important for the goals of this study.

This work is focused on the description of these problems in case of (two-loop) multifunctional filter structures, in order to identify uncertain (problematic) components and determine by how much particular parasitic component (modeling specific real part of impedance) influences the transfer function.

Typical values of attenuation in stop band (the worst situation is in case of band pass response at low frequencies) achievable by recently presented solutions are about 40 dB [3], [7], about 30 dB [8-9] or even only about 20 dB [2], [10], [11] which is really and practically unfavorable in many kinds of applications. Mainly band pass (BP) and high pass (HP) transfer functions are influenced in discussed solution. Many novel solutions employing different and also novel active elements are still affected similarly like in circuit solutions introduced above. Therefore, it is very current problem in design of current mode circuits. We usually have to respect some rules in design of active elements (in view of small signal parameters) applicable in these structures that lead to decreasing and reduction of these problems in stop band. Of course, also other than two-loop structures are influenced. One typical example is in [12].

There are many possible active elements suitable for analog signal processing [3]. We can introduce for example current conveyors [10], [13] which have been known for years and transconductors [13-14], current differencing transconductance amplifier (CDTA) [13], [15], current differencing buffered amplifier (CDBA) [13], current follower transconductance amplifier (CFTA) [13], [16], current conveyor transconductance amplifier (CCTA) [13], [17], etc.

Current Conveyor Transconductance Amplifier (CCTA) [17] element was chosen for its great current mode performance in active filters and also because it is available at our workplace as real device. This device contains low impedance current input X, high impedance voltage input Y, high impedance auxiliary port Z and high impedance output (or outputs in case of multiple-output variant). The construction of loop or multi-loop systems is very easy with minimum number of external passive components. Fig. 1 shows schematic symbol of CCTA, its internal principle, and main small-signal parasitic components causing significant problems in applications (with highlighted components). The presented structure contains just two outputs but we can use analogical principles to model more outputs. The following equations are valid for ideal model (Fig. 1b): $I_Y = 0$, $V_Y = V_X$, $I_Z = I_X$ and $I_{\pm x1,2} = \pm g_m V_Z$.

Small-signal parameters of the behavioral CCTA model extracted from simulations and measurements (several prototypes) [18] are (for two different internal topologies): R_Y = 2.5 or 5.2 MΩ, R_X = 15 or 240 Ω, $R_{x1,2}$ = 2.4 MΩ. However these parameters are not as important for further analyses as explained later. For further details see [18], unfortunately in Czech language only.

Frequency dependence of gain or transconductance is not modeled because it is not source of discussed influences. The main problems are caused by highlighted (in figures) components (real part of inp/out and high-impedance nodes impedances).

2. The two-loop KHN biquad

The universal structure of two-loop current-mode filter, well-known as derivation from KHN biquad [19], is widely used in many works [16]. There are two lossless integrators and additional multi-output follower (CCTA3). Desired transfer responses are obtained on particular outputs (low pass, band pass and high pass) thanks to this additional block and multi-output variants of CCTAs. No mirroring through grounded passive components (additional separating current-mode followers) is necessary, as for example in [20]. The circuit in Fig. 2 (without highlighted components) provides the following ideal transfer functions typical also for many similar and already published solutions utilizing for example Operational Transconductance Amplifiers (OTAs) [3], [11]:

$$K_{HP}(s)=\frac{-s^2}{s^2+\frac{g_{m1}}{C_1}s+\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (1)$$

$$K_{BP}(s)=\frac{\frac{g_{m1}}{C_1}s}{s^2+\frac{g_{m1}}{C_1}s+\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (2)$$

$$K_{LP}(s)=\frac{-\frac{g_{m2}g_{m3}}{C_1C_2}}{s^2+\frac{g_{m1}}{C_1}s+\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (3)$$

where pole frequency and quality factor are:

$$\omega_p=\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}},\ Q=\frac{C_1}{g_{m1}}\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}. \quad (4), (5)$$

3. Analysis of important parasitic small-signal influences

Significant problems (limited attenuation in stop bands) are originated mainly in high impedance nodes. Fig. 2 shows circuit structure and realization with significant parasitic components in important nodes (highlighted components). Parameters of filter, which were used in PSpice simulations with models of CCTA showed in Fig. 1c, were selected as: pole frequency $f_p = 4.23$ kHz, quality factor $Q = 1$, $C_1 = C_2 = 47$ nF and $g_{m1} = g_{m2} = g_{m3} = 1.25$ mS. The main intention of this work is to present important problems, caused by real resistive attributes of inputs and output, and their reasons, not to design novel high frequency filtering solution. Therefore actual values of f_p and Q (or approximation) are not so important. Cut-off frequency is so low in order to highlight analyzed effects.

Important problems (typical for many similar solutions) of produced transfer functions considering small-signal parasitic parameters are discussed in the following text in more detail. Expected impacts are also evaluated. First of all, input node where all current outputs are connected to low-impedance current input of $CCTA_3$ does not influence behavior because in almost all cases $R_{\pm x1} >> R_X$ and R_X represents overall resistance value of this node. Similar behavior is expected between current output +x and current input X of following CCTA element ($CCTA_1$ and $CCTA_2$). Other resistances are summarized to total node resistances/conductances referred as G_{p1}-G_{p3}. Particular values can be consequently calculated as (from the left side in Fig. 2): $G_{p3} = 1/R_{Z3} + 1/R_{-x3}$, $G_{p2} = 1/R_{Z2}$, $G_{p1} = 1/R_{Z1}$. Parasitic capacitances are not included in presented calculations because their impact on studied attenuations and other problems is minimal (minimal also due to designed low-frequency operational range) and their inclusion in analyzed equations make them hardly understandable and complicated for solution in designer's practice. In real applications, parasitic capacitances usually only decreases cut-off frequency and this effect is easily compensated by decreasing of working capacitors. Parasitic capacitances are included in Fig. 1 just for reference.

We focused our analysis on study of total node conductances/resistances G_{p1}-G_{p3}, because these values directly determine the lowest acceptable value of small-signal parameter (resistance of current output for example) of active device. We can find the impedance limits for particular criteria of minimal attenuation in stop band. In case of G_{p1} and G_{p2}, their values are dependent only on R_{z1} and R_{z2}. This is a specific advantage, because some already published structures use directly coupled blocks (it means that current output of previous component is directly connected to high-impedance input of following component, with grounded capacitor) [3], [11], [15] therefore G_p can be inappropriately increased externally by ports of two active elements.

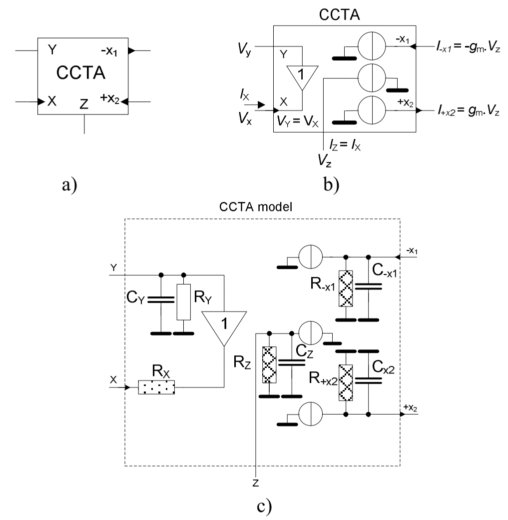


Fig. 1. Current conveyor transconductance amplifier (CCTA): a) symbol, b) ideal small-signal model and description, c) non-ideal model including important parasitic components (highlighted components)

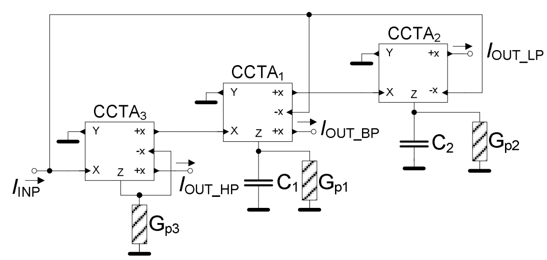


Fig. 2. Two-loop full KHN filter equivalent based on CCTAs with dominant parasitic influences in nodes (highlighted components)

Denominator of the transfer function that was influenced by above discussed small-signal parameters has the following form:

$$D(s)=s^2+\frac{g_{m3}\left(C_1G_{p2}+C_2G_{p1}\right)+G_{p3}\left(C_1G_{p2}+C_2G_{p1}\right)}{C_1C_2\left(g_{m3}+G_{p3}\right)}s+ \\ +\frac{g_{m3}\left(G_{p1}G_{p2}+g_{m1}G_{p2}+g_{m1}g_{m2}\right)+G_{p1}G_{p2}G_{p3}}{C_1C_2\left(g_{m3}+G_{p3}\right)}. \quad (6)$$

3.1. High pass filter response analysis

Real numerator (N) of the HP transfer function is as follows:

$$N^{*}_{HP}(s)=\left(\frac{g_{m3}}{g_{m3}+G_{p3}}\right)s^{2}+\frac{g_{m3}\left(C_{1}G_{p2}+C_{2}G_{p1}\right)}{C_{1}C_{2}\left(g_{m3}+G_{p3}\right)}s+ \\ +\frac{g_{m3}G_{p1}G_{p2}}{C_{1}C_{2}\left(g_{m3}+G_{p3}\right)}, \quad (7)$$

and it has two parasitic zeros:

$$z_{1}=-\frac{1}{R_{p1}C_{1}}\;, \qquad z_{2}=-\frac{1}{R_{p2}C_{2}}\;. \qquad (8), (9)$$

The limit gains of transfer function at high-frequencies (HF), i.e. in pass-band of HP filter, and at low frequencies (LF), i.e. in stop-band of HP filter, are given by:

$$K_{0}=\left|K^{*}_{HP\_HF}(\omega\to\infty)\right|=\lim_{\omega\to\infty}\frac{N^{*}_{HP}(s)}{D^{*}(s)}=\frac{g_{m3}}{g_{m3}+G_{p3}}, \quad (10)$$

$$K_{\min}=\left|K^{*}_{HP\_LF}(\omega\to 0)\right|=\lim_{\omega\to 0}\frac{N^{*}_{HP}(s)}{D^{*}(s)}= \\ =\frac{g_{m3}G_{p1}G_{p2}}{g_{m3}\left(G_{p1}G_{p2}+g_{m1}G_{p2}+g_{m1}g_{m2}\right)+G_{p1}G_{p2}G_{p3}}, \quad (11)$$

It is obvious that stop-band attenuation (and Q) is influenced both by R_{p1} and R_{p2}. Both these components have impact on zeros position. R_{p3} causes drop in pass-band gain, Q and small f_{p} changes. Details are obvious from Fig. 3. If these influences are combined, transfer function could be damaged.

3.2. Band pass filter response analysis

Real numerator of the BP transfer function has form:

$$N^{*}_{BP}(s)=g_{m1}g_{m3}\left(sC_{2}+G_{p2}\right), \quad (12)$$

and there is one parasitic zero:

$$z_{1}=-\frac{1}{R_{p2}C_{2}}, \quad (13)$$

Limit case of the transfer at low frequencies is:

$$K_{\min}=\left|K^{*}_{BP\_LF}(\omega\to 0)\right|=\lim_{\omega\to 0}\frac{N^{*}_{BP}(s)}{D^{*}(s)}= \\ =\frac{g_{m1}g_{m3}G_{p2}}{g_{m3}\left(G_{p1}G_{p2}+g_{m1}G_{p2}+g_{m1}g_{m2}\right)+G_{p1}G_{p2}G_{p3}}, \quad (14)$$

Simulation results are shown in Fig. 4. R_{p1} has main impact on pass band gain and Q. R_{p2} is main source of finite attenuation in stop band at low frequencies. Changes of R_{p3} caused f_{p} shift and small impact on Q.

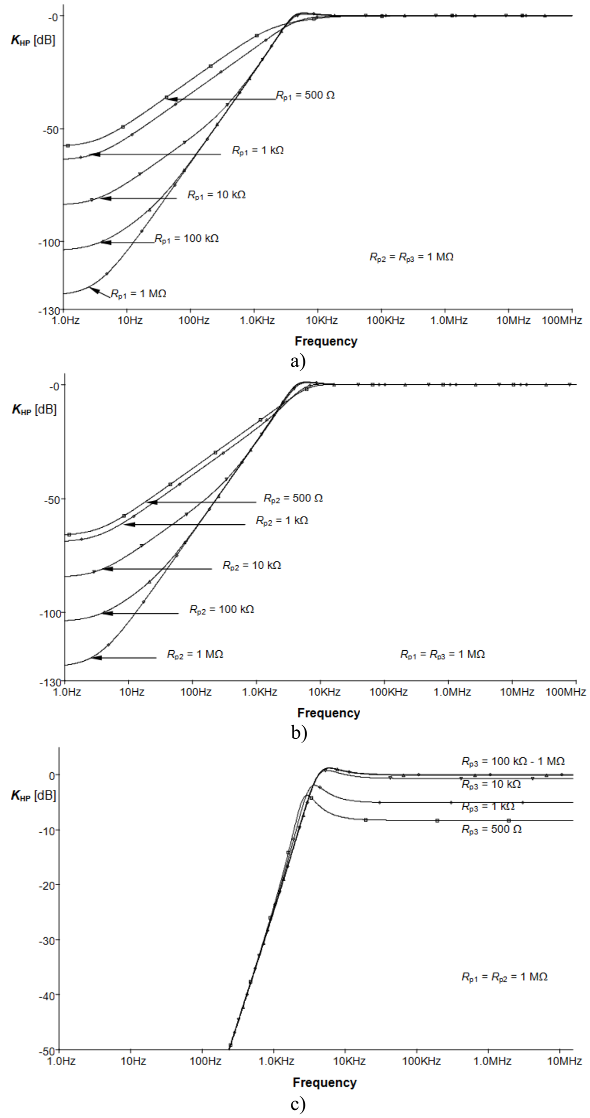


Fig. 3. Impact of parasitic impedances on HP response: a) R_{p1} separately, b) R_{p2} separately, c) R_{p3} separately

3.3. Low pass filter response analysis

Numerator of the LP response is in form:

$$N^{*}_{LP}(s)=g_{m1}g_{m2}g_{m3}, \quad (15)$$

This transfer function is not disturbed by parasitic zero in this particular case. Limited gain of the pass band transfer (low frequencies) is given by the following equation:

$$K_{0}=\left|K^{*}_{LP\_LF}(\omega\to 0)\right|=\lim_{\omega\to 0}\frac{N^{*}_{LP}(s)}{D^{*}(s)}= \\ =\frac{g_{m1}g_{m2}g_{m3}}{g_{m3}\left(G_{p1}G_{p2}+g_{m1}G_{p2}+g_{m1}g_{m2}\right)+G_{p1}G_{p2}G_{p3}}. \quad (16)$$

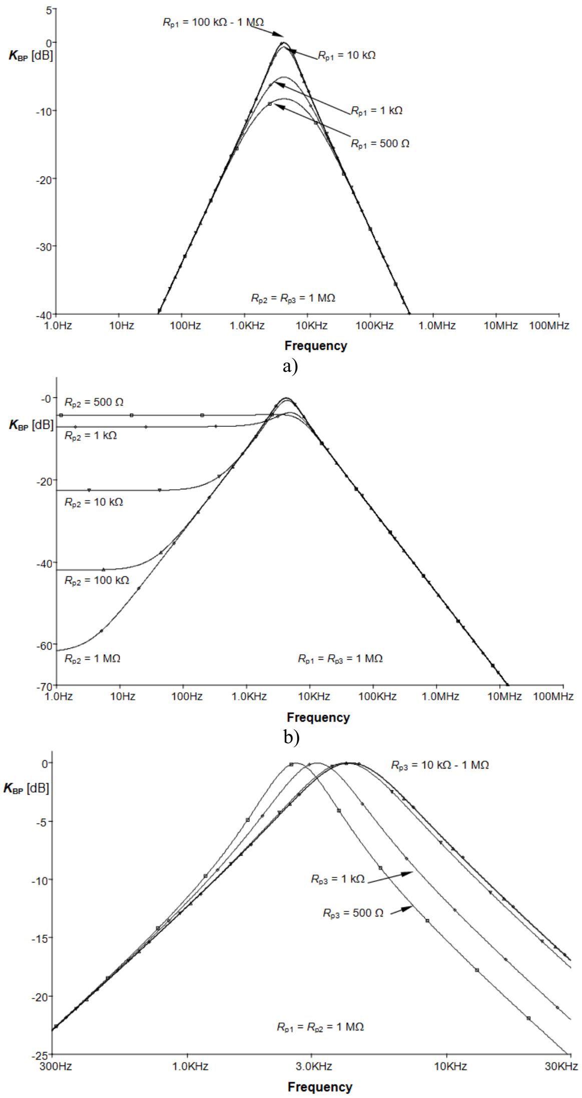


Fig. 4. Impact of parasitic impedances on BP response: a) R_{p1} separately, b) R_{p2} separately, c) R_{p3} separately

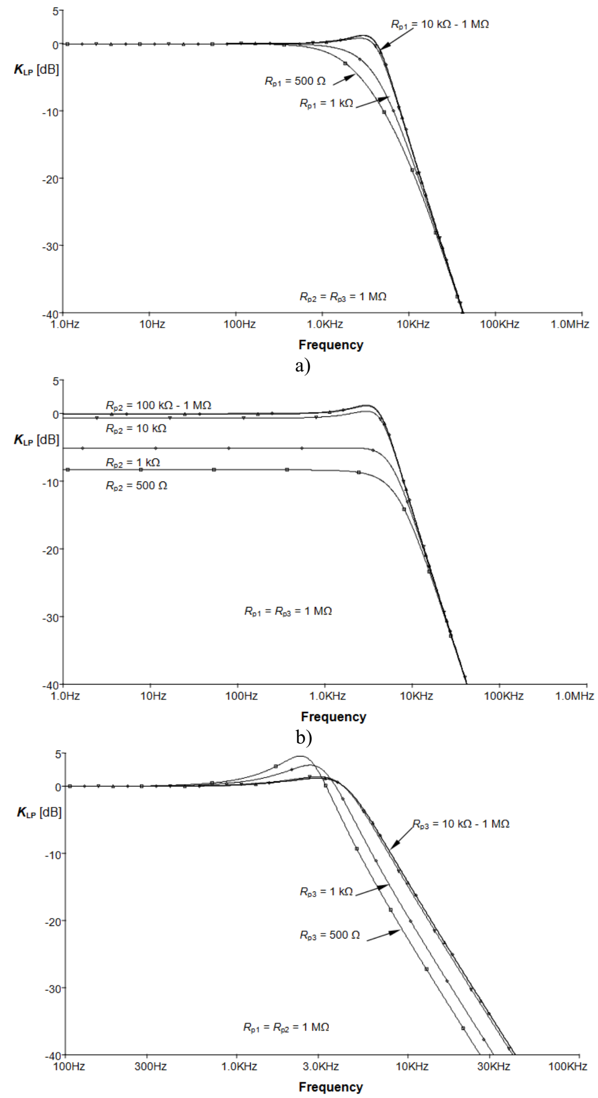


Fig. 5. Impact of parasitic impedances on LP response: a) R_{p1} separately, b) R_{p2} separately, c) R_{p3} separately

Simulation results of LP transfer function are shown in Fig. 5. R_{p1} causes only problems with Q but impact on pass-band gain is minimal. Main source of problems with pass-band gain is R_{p2} and it also affects Q. R_{p3} influences f_p and Q but pass band gain is not affected.

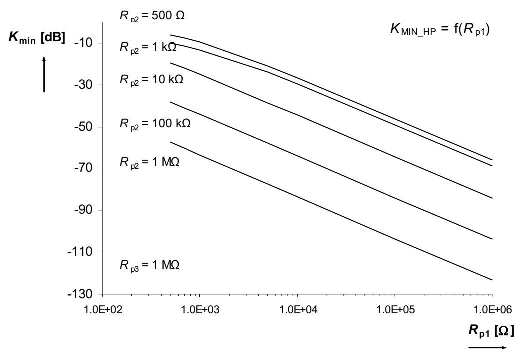
4. Discussion

We can suppose that each used active element has the same or very similar features (given by manufacture tolerances) as the rest of the same type of active elements in the circuit. In the following figures, there are cases when parameter could not be similar or close to each other or are even quite different.

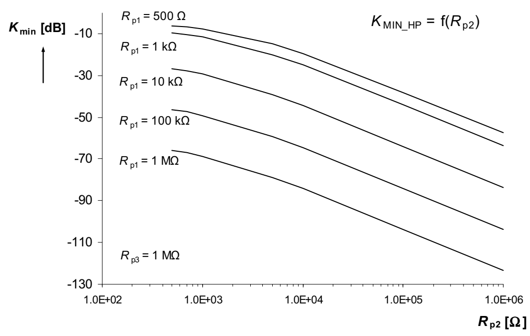
In case of HP response, there is a problem with stop band attenuation. We can suppose that all parasitic components ($R_{p1,2,3}$) influence filter properties simultaneously. Then, there is $R_{p1,2,3} > 30$ kΩ requested for good attenuation below 60 dB (as is obvious from the following **Fig. 6**). However, analysis results show that main impact on stop band attenuation at HP response has R_{p1} and R_{p2}. Influence of R_{p3} is insignificant.

In case of BP response, R_{p1} has impact on pass band transfer. Sufficient value for neglectable influence is over 10 kΩ. R_{p3} caused shift of the f_p frequency and changes of Q. For more than 10 kΩ this is insignificant problem. However, important problem is in finite attenuation in stop band caused by R_{p2} where desired attenuation over 60 dB is achieved for $R_{p2} > 800$ kΩ.

At the LP response, R_{p2} causes pass band K_0 drop ($R_{p2} > 50$–80 kΩ - for $K_0 < 0.1$ dB). R_{p1} causes problems with Q but it is neglectable for $R_{p1} > 30$ kΩ. R_{p3} affects Q and K_0 but for $R_{p3} > 20$ kΩ it is irrelevant.



a)



b)

Fig. 6. Dependence of maximal attenuation of the HP response on: a) R_{p1}, b) R_{p2}

4. Conclusion

Problems of many (almost all) modern active current-mode biquads were discussed in presented paper. Main problem of particular filtering application is finite attenuation in stop band. This was clarified and documented by symbolical and numerical results. These problems were discussed on three filtering functions. The obtained results are useful for designer of current mode biquads and circuits because these problems in presented two-loop filter based on CCTA integrators are also applicable to similar circuits with other active elements. However, in presented research there is still space for additional future improvements (we can consider also inequalities of g_m, non-unity current followers, from very complex view also nonlinearities, etc.).

7. References

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