SOME PRACTICAL PROBLEMS IN OTA-C FILTERS RELATED WITH PARASITIC CAPACITANCES

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Abstract

Some effects of parasitic capacitances on operational transconductance amplifier - capacitor (OTA-C) filters are studied. In particular, it is shown that serious stability problems may occur if passive filters containing capacitor loops of inductor cut-sets (structures with non-observable poles at infinity) are simulated by OTA-C structures with all the capacitors grounded. Structures that avoid those problematic effects are proposed for the realization of these filters.

Introduction

Initially, considerations about OTA-C structures realizing low-pass and band-pass filters, the most usual ones, will be made. Some OTA-C structures derived from passive prototypes for the realization of these filters were proposed in [1-5]. With ideal OTAs and no parasitic elements in the circuit, the most important criteria to be used to evaluate the quality of the realizations are the preservation of the sensitivity characteristics of the passive prototype, and the size (mainly the number of OTAs) of the structures. This is justified by two facts: first, sensitivities must be kept as low as possible because automatic tuning in OTA-C structures is easy only in frequency. It is not simple to tune passive filter simulation structures to correct distortions caused by errors in capacitance or transconductance ratios, and the idea is to rely in the low sensitivities to turn that tuning unnecessary. Second, the main application of OTA-C filters is in mixed analog-digital ICs, where the filter function is only a small part of the IC function, and it must occupy the smallest possible area and consume little power. In [1-3] emphasis was given to these aspects, and secondly to realizations with all the capacitors grounded. The only non ideal aspect examined was the problem with non-observable poles at DC in band-pass structures [2-3], that turns impractical the realization of band-pass filters having finite transmission zeros with all the capacitors grounded and optimal sensitivity preservation. The problem is caused by the presence of inductor loops or capacitor cut-sets in the passive band-pass prototype, that when simulated in the active realization, lead to structures in which the output offset current of the OTAs can charge continuously a capacitor cut-set until saturation is reached.

When a really practical filter structure is searched, it must be insensitive to parasitic circuit elements and to the frequency response of the OTAs, and some additional considerations must be made.

The problem with non-observable poles at infinity

A previously unnoted subtle problem arises when a passive low-pass or band-pass filter with finite transmission zeros is simulated by a structure with all the capacitors grounded, and with a one-to-one correspondence among capacitors in the OTA-C simulation and reactive elements in the passive structure. The passive prototype always present capacitor loops (or inductor cut-sets) realizing non-observable poles at infinity that are broken up in the OTA-C simulation. In the simulations discussed in [2,3], these circuit entities are always transformed into capacitor loops, with the floating capacitors simulated by grounded capacitors connected to the remaining of the loop by OTA structures that always present a node without any capacitance to ground. Examples are the structures in figs. 2B and 2C in [3], and 4b, 6a and 6b in [2] (also 3b, even with floating capacitors). From this node, the element realizing the floating capacitor is always seen as a grounded inductor, sometimes in an LC series tank (as in the example below). A small parasitic capacitance from that node to ground is in parallel with this circuit and is equivalent in the passive prototype to a small inductor in series with a capacitor loop (or a small capacitor in parallel with an inductor cut-set). This new element eliminates the pole-zero cancellation at infinity caused by the loop (or cut-set) and introduces a new pole by itself. The effect is that a single parasitic capacitance introduces two new high-frequency poles in the filter. In the passive prototype it can be observed that a small positive inductor in series with a capacitor loop (or the dual) introduces a pair of complex poles with very high Q in high frequency because it resonates with very low impedance capacitors that virtually short-circuit the filter terminations and remaining inductors at the resonance frequency. With some structures, it is also possible to this parasitic capacitance to be equivalent to a negative inductor (or capacitor) in the same situation. The effect is the creation of two poles in symmetrical positions in the real axis, and the resulting filter is unstable. Both situations can also occur in most other OTA-C simulations of passive filters proposed

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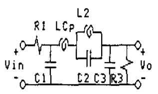
in the literature [4-5].

In the case of parasitic complex poles, with ideal OTAs the observed effect is of one or more sharp peaks in the high-frequency rejection band, accompanied by sharp -180 degrees phase transitions. When an excess-phase is taken into account in the OTAs transfer function, however, the complex high-frequency poles are easily moved to the right complex half-plane, turning the filter unstable. The effect can be observed even in discrete realizations of these OTA-C filters, where parasitic capacitances are very small compared to the filter capacitors. When the filters are tuned to higher frequencies, they begin to oscillate in high frequency even when the effects of excess-phase in the passband are still negligible. In integrated versions, where parasitic capacitances are only one or two magnitude orders lower than the filter capacitors, this problem may be much more serious. It must be noted that the ratio of the resonance frequency to the passband end frequency is proportional to the square root of the ratio between the filter capacitors and the parasitic capacitances. In integrated realizations this ratio is low, and so the oscillation frequency is sufficiently low to the problem occur, being not masked or avoided by circuit losses at high frequency, as may happen in discrete versions.

The instability caused by real axis pole pairs can be detected in frequency response simulations by a smooth transition of -40 dB/decade in the gain curve, without effect in the shape of the phase curve.



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C1 = 1.90941
L2 = 0.90421
C2 = 0.14536
C3 = 1.90941
Cp = 0.01

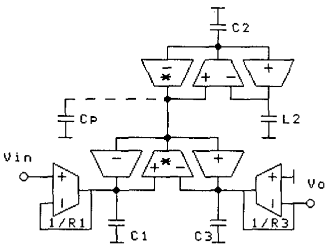

Fig. 1 - Normalized OTA-C filter simulation for an elliptic low-pass filter (left) with 1 dB passband ripple from 0 to 1 rad/s and 40 dB minimum attenuation at the stopband. A small parasitic capacitor, Cp, is considered connected as shown, being equivalent to the parasitic inductor LCp shown in the prototype filter. In this and in the other drawings, the transconductances are unitary unless when otherwise indicated.

For example, fig. 1 shows the realization of a normalized 3rd order elliptic filter using the technique proposed in [2]. The ideal frequency response is shown in fig. 2, curve (a). A small parasitic capacitor introduced in the node without capacitance to ground has the effect in the frequency response shown in curve (b): high-Q complex poles are created at high frequency. A simulation (not presented) shows that with less than 0.1 degree excess-phase in the transconductances at the passband border, the complex poles in curve (b) are moved to the right half-plane, instabilizing the filter. If the polarities of the two marked OTAs are reversed, the ideal response is not changed, but now the introduction of the parasitic capacitor has the effect shown in curve (c): the effect of the presence of a pair of symmetrical real axis poles in high frequency can be observed.

These considerations may turn impractical the direct simulation with grounded capacitors of any passive filter presenting capacitor loops or inductor cut-sets, including the ones with best sensitivity preservation [2]. The real axis symmetrical poles can always be avoided by proper ordering of OTA polarities (as in [1-3]), but the problem of the high-Q complex poles remains. Their effect can be minimized by adding losses to the filter, or by using an adequate compensation in the OTAs to decrease the Q of the parasitic poles, but this remains to be studied.

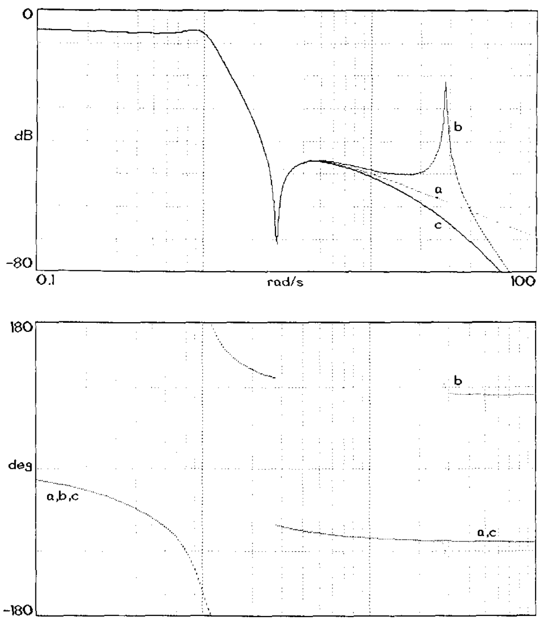

Fig. 2 - Frequency responses obtained for the OTA-C filter in fig. 1. (a) With ideal OTAs and no parasitic capacitances. (b) Considering the parasitic capacitor Cp. (c) Reversing the polarities of the marked OTAs.

Additional problems related to parasitic capacitances

Due to the low ratio between filter capacitances and parasitic capacitances in integrated realizations, at least two more problems can be identified. The first is the formation of parasitic transmission zeros: Differential-input OTAS with both inputs floating put a parasitic capacitance between two nodes, that when returned to the equivalent in the passive prototype, in most cases is seen to be in the right place to produce a pair of jw axis transmission zeros [7,9]. Examples are several structures in [1-3]. The ratio of the frequency of these zeros to the end of the passband is also proportional to the square root of the ratio of the filter capacitors to the parasitic capacitances, being low in integrated realizations. This problem is not very serious, as it cannot unstabilize the filter, but the distortion in the filter characteristics may be significative. If the filter has transmission zeros and floating capacitors [1], the effect of the parasitic capacitances can be mostly absorbed by discounting their values from the capacitors realizing the zeros.

The second problem is more serious: If the OTA-C structure has internal nodes without any capacitor connected and with resistive impedance, a capacitance from one of these nodes to ground introduces another pole, usually in the negative real axis, to the filter transfer function. The effect is resembling of the one of a high-frequency pole (or excess-phase) in an OTA transconductance: the filter poles and zeros are moved to the right side. In integrated filters, the introduced poles can easily be of lower frequency than the equivalent ones introduced by the OTAs, and the effect of parasitic capacitances increasing the Q of the filter poles, possibly causing instability, may be more significative than the effect of the excess-phase of the transconductances. The structures without non-observable poles presented in [1,3] may present this problem, as they use resistive nodes to add currents. This problem can be reduced by the use of low impedance levels in the resistive nodes and by techniques similar to the ones used to compensate for the excess-phase of the transconductances.

Effect of the frequency response of the OTAs

OTAs are usually sufficiently simple so that the frequency range in which they are virtually ideal elements is much higher than the useful frequency range of comparable operational amplifiers, for example. Even so, OTA-C simulations of passive filters are rather sensitive to phase deviations in the transconductances [6]. Simulations shows that a 1 degree deviation in phase is sufficient to severely distort the characteristics of most filters, moving to the right side the poles and zeros, and the problem only worsts as the order of the filter and the Q of the poles increase. The effect can be effectively corrected by predistortion of the passive prototype, or even some tuning, but it appears to be better to correct the phase deviation of the transconductances using some form of internal compensation in the OTAs [10] or external active compensation [7]. As the error introduced is proportional to the number of OTAs in the circuit, specially OTAs forming loops, it is desirable to use circuits as simple as possible. The effect of resistive losses in the circuit is usually opposite to the effect of parasitic capacitances and transconductance excess-phase, being not a so serious problem [7].

Practical OTA-C filters

From the considerations above, some conclusions can be obtained about what structures are the most practical to the construction of OTA-C filters by the simulation of passive prototypes.

For low-pass filters, there are no problems with non-observable poles at DC, and only the introduction of new high-frequency poles by parasitic capacitances shall be avoided. Capacitor loops or inductor cut-sets can be simulated, in an one capacitor per element basis, only by capacitor loops. The structures proposed in [1] are acceptable. In the structures that preserve all the passive elements in [1], if single-input OTAs are used, as needed for dynamic range equalization, all the important parasitic capacitances (OTA inputs and outputs, and bottom plate capacitance of floating capacitors) can be absorbed by the filter capacitors (if they are predictable, linear, and not too high). Even with differential-input OTAS, it can be observed that no parasitic capacitance can introduce new poles in those structures. For realizations with all the capacitors grounded and finite transmission zeros, the structures without non-observable poles in [1] may be an alternative. In those structures, several parasitic capacitances cannot be absorbed, but they can only introduce new poles at the negative real axis. The structures suggested in [2] (see example above) for filters with finite transmission zeros, although being the ones that best preserve the sensitivity characteristics of the passive prototype, always present the problem with non-observable poles at infinity. May be used only if parasitic capacitances are small, so the circuit losses in high-frequency can lower the Q of the introduced poles, and an adequate compensation for the OTAs frequency response is possible.

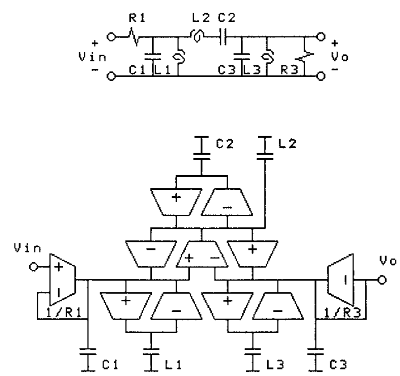

Fig. 3 - OTA-C simulation for a passive all-pole band-pass filter.

For band-pass filters, non-observable poles at DC and infinity may cause problems. For filters with finite transmission zeros, the less problematic structure is the structure without non-observable poles presented in [3]. It cannot present problems of DC saturation or high-frequency oscillation. It has resistive nodes, however, and a great number of OTAs. The other structures proposed in [2-5] for band-pass filters with finite transmission zeros all present problems with non-observable poles at DC, infinity, or both. For all-pole approximations, the method presented in [3] can be used directly, resulting a structure like the one in fig. 3, that is also equivalent to an unbalanced version of the structure proposed in [6] for ladder simulation.

OTA-C-OA filters

Another solution to the problem of parasitic capacitances, is the use of structures based on Miller integrators made with operational amplifiers (OA), using the equivalence shown in fig. 4.

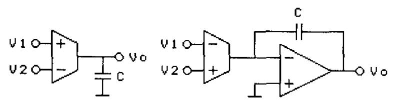

Fig. 4 - Equivalence between an OTA-C integrator (left) and an OTA-C-OA Miller integrator (right).

All the parasitic capacitances to ground are then connected to virtual grounds or op. amp. outputs, resulting a circuit very insensitive to parasitic capacitances. A realization for a 3rd order elliptic low-pass filter is shown in fig. 5. The circuit is a conventional RC-active signal-flow graph realization for this kind of filter, with resistors replaced by OTAs. This structure is similar to the one proposed in [8], but with finite transmission zeros. The increase in complexity is not high, as the operational amplifiers may be very simple. It is interesting to note that, as the op. amp. inputs are fed by current sources instead of resistors, their input offset voltages are not important. The realization does not present problems with non-observable poles at infinity, because the capacitor loops of the passive prototype continue to exist, although in a modified form.

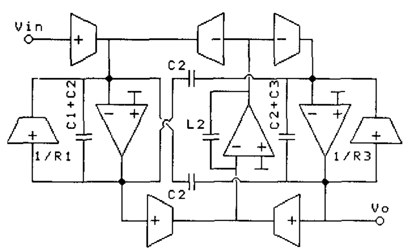

Fig. 5 - OTA-C-OA simulation for the 3th order elliptic low-pass filter shown in fig. 1.

Conclusions

It was shown that the problem with parasitic capacitances in OTA-C continuous-time filters may be very serious, specially in the simulation of passive filters with finite transmission zeros, and that attempts to partially solve the problem by the use of structures with all the capacitors grounded may introduce worse problems. Solutions may be to restrict OTA-C simulations to all-pole filters, the use of structures that can absorb all the important parasitic capacitances in the filter capacitors, structures without non-observable poles, or the use of parasitic-insensitive structures incorporating simple operational amplifiers.

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