Reactive Loop Elimination and the Use of Special Approximations in the Design of OTA-C Filters

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***Abstract*—The use of special approximations in the design of passive filters to be used as prototypes for OTA-C realizations allows the elimination of multiple loops of reactive elements that appear in usual LC ladder filters with finite transmission zeros. This leads to more efficient active simulations, where problems with floating capacitors, DC or high-frequency instability, or limited operating frequency are avoided.**

I. Introduction

The realization of active filters by the simulation of LC doubly terminated prototypes designed for maximum power transfer is recognized as the best, when sensitivity of the filter transfer function to variations in the element values of the realization is to be kept as low as possible.

Several methods can be used in the generation of an OTA-C (using Operational Transconductance Amplifiers and Capacitors) simulation of a given passive prototype [1][2], but due to the great simplicity of the technique, the final results are almost always equivalent.

Polynomial filter prototypes can be easily simulated with good results. There are problems, however, if the filter approximation presents finite transmission zeros. With usual approximations, in the passive prototype this always causes the existence of capacitor loops, inductor loops, or loops of series LC tanks tuned to the same frequency (in band-reject filters), or the dual versions of these structures.

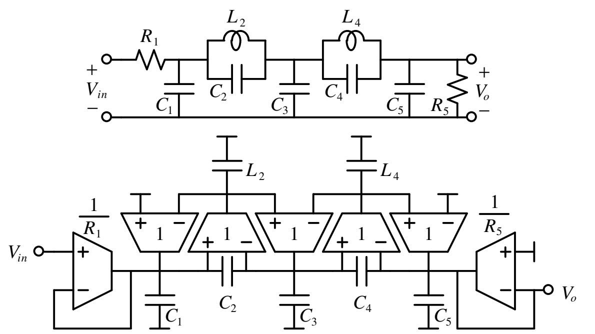

Fig. 1. Passive prototype and normalized OTA-C structure with multiple capacitor loops for a 5th-order elliptic low-pass filter.

The presence of capacitor loops (or inductor cut-sets) in the prototype results in OTA-C circuits presenting capacitor loops. The loops always include floating capacitors, a problem in most integration technologies due to the presence of significant parasitic capacitances, with values uncorrelated to the main capacitances or even nonlinear. Filters where capacitor loops of the prototype are retained (or inductor cut-sets dualized) are simple [1] (fig. 1), but can be successfully built only at the expense of careful control of parasitic capacitance values.

An inductor loop (or capacitor cut-set) in the prototype results in a nonobservable DC current (or voltage) that can circulate in the loop (or be retained in the cut-set), that is simulated as an uncontrolled DC voltage in some part of the OTA-C simulation. These circuits must be eliminated or simulated by capacitor cut-sets (that include floating capacitors), otherwise offset currents can cause the growing of that voltage until the saturation of some of the OTAs is reached.

The elimination of capacitor loops in the OTA-C simulation simplifies the transformation of a low-pass filter into other forms (band-pass, high-pass, band-reject). It is enough to apply the adequate reactance transformation to the grounded capacitors in the transformed low-pass OTA-C prototype, and realize the resulting inductors using OTA gyrators and capacitors. Problems with natural frequencies at DC (in high-pass or band-pass filters) or in the $j\omega$ axis (a problem in band-reject filters) are completely avoided.

This work first examines two techniques for the elimination of capacitor loops. The elimination can be made in the OTA-C simulation of the prototype, case that covers the presence of inductor cut-sets in the prototype. It is concluded that realizations with best performance are obtainable when these circuits are in the simplest, single loop, form. Modified approximations are then proposed, that result in LC doubly terminated ladder prototypes with only simple capacitor loops or inductor cut-sets. Finally, the elimination of inductor loops is discussed, also with two approaches that complement the methods shown for capacitor loops. The elimination can also be done in an OTA-C simulation (with some inductors retained), case that covers the presence of capacitor cut-sets in the prototype. In this case, there is no need for special approximations, since the simplest method is applicable without problems to multiple inductor loops.

II Elimination of Capacitor Loops

It is possible to eliminate floating capacitors in capacitor loops by inserting OTA gyrators in the circuit, dualizing the floating capacitors into inductors, that are then dualized again into grounded capacitors [2]. This technique is problematic, however, because extra natural frequencies are created when the capacitor loops are broken. Parasitic capacitances in the resulting floating nodes can create high-Q complex natural frequencies [3], and can cause instability when in combination with a small excess of phase in the OTAs transconductances.

A more practical solution is to modify the circuit in a way that retains the filter operation, but eliminates the superfluous capacitors. Two methods were previously proposed for this purpose [4][5], sumarized here in a somewhat different point of view:

Voltage-controlled Norton equivalent

Consider the simple capacitor loop in fig. 2. It is equivalent to the circuit in fig. 3, where the original circuit was replaced by its *Y* parameters equivalent.

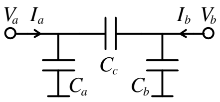

Fig. 2. Simple capacitor loop.

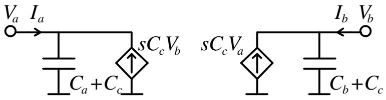

Fig. 3. Voltage-controlled Norton equivalent, or *Y* parameters equivalent, for a capacitor loop.

A practical OTA-C implementation is obtained by the observation that the currents fed by the two transcapacitances are proportional to the currents in the two capacitors. Figure 4 shows (in schematic form) a possible implementation, where the OTAs that feed the loop (assumed as one for each side) are split in a transconductor input stage and a current-controlled current source output stage with two scaled outputs. Other implementations are also possible [4].

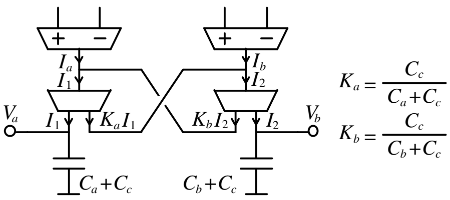

Fig. 4. Schematic representation of an implementation of the voltage-controlled Norton equivalent of a capacitor loop.

This procedure is directly applicable to multiple loops. The loop equivalents are uncoupled, and can be obtained independently. The implementation requires, however, two-stages OTAs, or other variations that always present internal nodes, and the correspondent parasitic poles, what may turn these structures unsuitable for high-frequency filters unless some form of frequency response compensation is used.

Current-controlled Norton equivalent

Another equivalent for the circuit in fig. 2 is shown in fig. 5. It is equivalent to the *Z* parameters representation with Norton equivalents applied at the two branches.

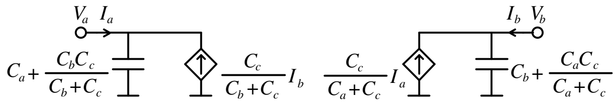

Fig. 5. Current-controlled Norton equivalent for a capacitor loop.

An OTA-C implementation is shown in fig. 6 [5]. Each OTA feeding one side of the loop has added a new scaled output. Single-stage OTAs, without internal nodes, can be used if the entire OTAs are duplicated. This is an important characteristic for high-frequency filters, because the creation of parasitic poles by stray capacitances in internal nodes is avoided.

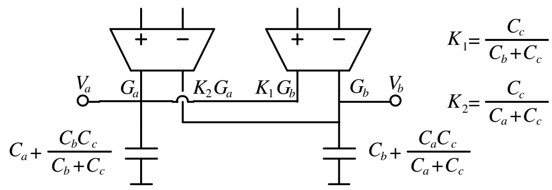

Fig. 6. Implementation of the current-controlled Norton equivalent for a capacitor loop.

This procedure can also be applied to multiple connected loops, but for this each OTA must have a number of outputs equal to the number of grounded capacitors, and the values of the new capacitors and scaling constants depend on the number of loops. Considering the sensitivity characteristics, the resulting circuits are generally acceptable in the passband, with some degradation in the stopband, mainly due to the large number of elements involved in the formation of the transmission zeros. The application of the procedure to multiple connected loops may result in high dispersion of transconductance values, due to the weak coupling among the extremes of the circuit. For simple loops, this is a simple and effective method for capacitor loop elimination.

III. Filters with Simple Capacitor Loops Obtained from Special Approximations

Usual elliptic or Inverse Chebyshev low-pass filters present the maximum possible number of finite transmission zeros. This results in LC ladder structures presenting several interconnected capacitor loops (or inductor cut-sets in the dual form), that in the OTA-C version result in structures like the one in fig. 1. If special approximations are used, where the number of finite transmission zeros is not maximum, a small reduction of selectivity results, but the loops and cut-sets can be kept separated in the LC structure (see fig. 7), and eliminated by the simplest form of the current-controlled Norton equivalent described above.

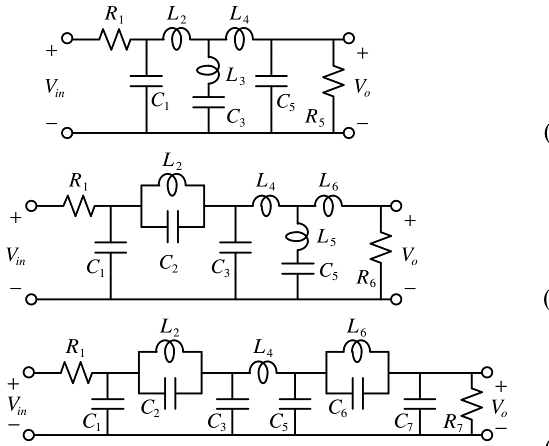

Fig. 7. Some LC doubly terminated structures for low-pass filters with separated capacitor loops or inductor cut-sets. (a) 5th-order with only 2 finite transmission zeros (the normal is 4). (b) 6th-order with 4 finite transmission zeros (the maximum possible for LC doubly terminated realization). (c) 7th-order with only 4 finite transmission zeros (the normal is 6).

Approximations for these filters can be obtained by the application of Moebius transformations [6] to usual approximations, or by direct optimization [7]. In appendix A, tables of some low-pass filter prototypes obtained from modified approximations are included.

$C_a=C_1+(C_2//C_3)$ $C_b=C_3+(C_2//C_1)$ $C_c=C_5+(C_6//C_7)$ $C_d=C_7+(C_5//C_6)$
$G_1=C_2/(C_1+C_2)$ $G_2=1$ $G_3=1$ $G_4=C_2/(C_1+C_2)$
$G_5=C_2/(C_3+C_2)$ $G_6=1$ $G_7=1$ $G_8=C_6/(C_5+C_6)$
$G_9=C_6/(C_7+C_6)$ $G_{10}=1$ $G_{11}=C_6/(C_7+C_6)$ $G_{12}=1$

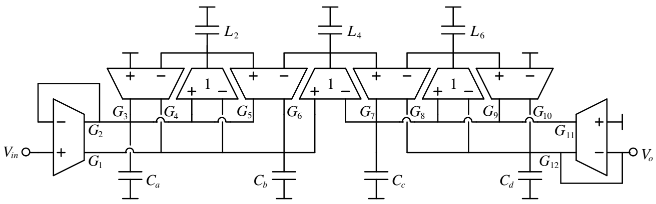

Fig. 8. Normalized OTA-C simulation of the structure in fig. 7c (with $R_1=R_7=1$), with the capacitor loops eliminated.

As an example, fig. 8 shows a normalized OTA-C realization for a 7th-order filter, obtained from a prototype with the structure in fig. 7c. The normalized filter presents 1 dB passband ripple and 50 dB minimum stopband attenuation (Values in table III). The OTA-C realization was obtained by the application of the current-controlled Norton equivalent to the capacitor loops that result from the direct simulation of the prototype.

IV ELIMINATION OF INDUCTOR LOOPS

If the prototype still presents inductor loops (or capacitor cut-sets in the dual version), as can happen in a filter not obtained from a reactance transformation of a low-pass prototype, or if for some reason the low-pass prototype has its capacitor loops or inductor cut-sets retained, these structures can be eliminated in the OTA-C version by procedures similar to the two methods shown for the elimination of capacitor loops. The first one is of common use in active simulations of passive filters, The second is new:

Voltage-controlled Thévenin equivalent

Consider the simple inductor loop in fig. 9. It is equivalent to the circuit in fig. 10, where the original circuit was replaced by its Y parameters equivalent, and Thévenin equivalents were applied to the resulting branches.

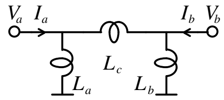

Fig. 9. Simple inductor loop.

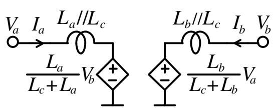

Fig. 10. Voltage-controlled Thévenin equivalent of an inductor loop.

The OTA-C simulation of this circuit is a direct dualization (fig. 11). The extension to multiple connected loops is trivial.

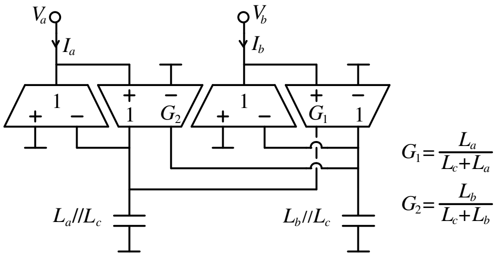

Fig. 11. OTA-C implementation of the voltage-controlled Thévenin equivalent for a simple inductor loop.

Current-controlled Thévenin equivalent

Another equivalent for the inductor loop in fig. 9 can be obtained from its Z parameters (fig. 12). Observing that the voltages at the controlled sources are proportional to the voltages over the inductors, and dualizing the resulting circuit, an OTA-C simulation is obtained, using the same idea of the current-controlled Norton equivalent. A schematic representation is shown in fig. 13. For multiple connected loops, the element values must be recomputed.

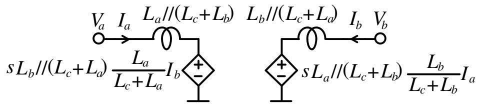

Fig. 12. Current-controlled Thévenin equivalent, or Z parameters equivalent, for an inductor loop.

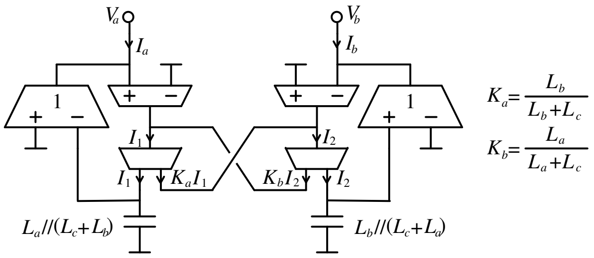

Fig. 13. Schematic representation of the OTA-C realization of the current-controlled Thévenin equivalent for an inductor loop.

V. Conclusion

Methods for the elimination of capacitor or inductor loops in passive prototypes for OTA-C filters were described. The four methods described were classified as Norton or Thévenin equivalents, voltage or current-controlled. The elimination of capacitor loops is the most important case, and the most convenient realizations are obtained if special approximations that allow realizations with only simple loops are used.

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Appendix A

In this appendix, some tables of LC doubly terminated prototype filters with simple capacitor loops are listed. Filters of orders 5, 6, and 7, are listed in tables I, II, and III, respectively. The structures are the ones in fig. 7. Each table lists the element values for a fixed minimum stopband attenuation (Amin, dB), and five values of the maximum passband attenuation (Amax, dB). The terminations for the odd-order filters are unitary. All the approximations present equal-ripple passband and stopband, and are as selective as possible.

TABLE I
5TH ORDER FILTERS (FIG. 7A). AMIN=40 DB.

Amax	L/C 1	L/C 2	L/C 3	L/C 4	L/C 5
0.1		1.1915	0.2450	1.1915	
	1.1615		1.4647		1.1615
0.2		1.1480	0.2568	1.1480	
	1.3551		1.5606		1.3551
0 5		1.0355	0.2647	1.0355	
	1.7233		1.7452		1.7233
1.0		0.9018	0.2612	0.9018	
	2.1548		1.9664		2.1548
1.5		0.8033	0.2539	0.8033	
	2.5178		2.1540		2.5178

TABLE II
6TH ORDER FILTERS (FIG. 7B). AMIN=40 DB.

Amax	Rg/Rl	L/C 1	L/C 2	L/C 3	L/C 4	L/C 5	L/C 6
0.1	1.1642		0.7768		1.6146	0.3370	0.7443
	0.8590	0.4985	0.8186	1.4604		1.1768	
0.2	1.2404		0.7673		1.6229	0.3657	0.8169
	0.8062	0.5647	0.8855	1.4560		1.1864	
0.5	1.4086		0.7377		1.6223	0.4123	0.9140
	0.7099	0.6530	0.9994	1.4387		1.1823	
1.0	1.6309		0.6987		1.6119	0.4577	0.9814
	0.6132	0.7131	1.1180	1.4162		1.1627	
1.5	1.8308		0.6670		1.6011	0.4908	1.0146
	0.5462	0.7415	1.2099	1.3989		1.1424	

TABLE III
7TH ORDER FILTERS (FIG. 7C). AMIN=50 DB.

Amax	L/C 1	L/C 2	L/C 3	L/C 4	L/C 5	L/C 6	L/C 7
0.1		0.6956		1.6312		0.9709	
	0.6019	0.9053	1.7334		1.8740	0.4503	0.8336
0.2		0.6516		1.5480		0.9204	
	0.7301	1.0239	1.8409		2.0036	0.5114	0.9806
0.5		0.5617		1.3792		0.8110	
	0.9645	1.2766	2.0684		2.2727	0.6388	1.2553
1.0		0.4682		1.1992		0.6919	
	1.2257	1.6137	2.3630		2.6160	0.8047	1.5691
1.5		0.4040		1.0717		0.6078	
	1.4361	1.9274	2.6253		2.9197	0.9563	1.8272