Generation of equivalent forms of operational trans-conductance amplifier-RC sinusoidal oscillators: the nullor approach

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Abstract: It has been shown in two earlier papers published from this study that corresponding to a given single-operational trans-conductance amplifier (single-OTA)-RC and dual-OTA-RC sinusoidal oscillators, there are three other structurally distinct equivalent forms having the same characteristic equation, one of which employs both grounded capacitors (GC). In this study, an earlier nullor-based theory of generating equivalent op-amp oscillator circuits, proposed by the first author, is extended to derive equivalent OTA-RC circuits which discloses the existence of an additional number of equivalent forms for the same given OTA-RC oscillators than those predicted by the quoted earlier works, and thereby considerably enlarging the set of equivalents of a given OTA-RC oscillator. Furthermore, the presented nullor-based theory of generating equivalent OTA-RC oscillators results in three additional interesting outcomes: (i) the revelation that corresponding to any given OTA-RC oscillator there are two 'both-GC' oscillators (and not merely one, as derived in the quoted earlier works); (ii) the availability of explicit current outputs in several of the derived equivalents and (iii) the realisability explicit-current-output 'quadrature oscillators' in some of the generated equivalent oscillators. The workability of the generated equivalent OTA-RC oscillators has been verified by SPICE simulations, based on CMOS OTAs using 0.18 μm CMOS technology process parameters, and some sample results are given.

1 Introduction

Operational transconductor amplifiers (OTAs)-based oscillators using only capacitors (OTA-Cs) or using resistance capacitance (RC) elements (OTA-RC) have been widely investigated because of the availability of electronic tunability of the oscillation frequency in such oscillators, for instance see [1–32] and the references cited therein. In [33], it was shown that corresponding to any given single-OTA-RC sinusoidal oscillator, there are three other structurally distinct equivalent forms [having the same characteristic equation (CE)] one of which employs both grounded capacitors (GC) as preferred for IC implementation [34]. Similarly, in [35] it was demonstrated, through five theorems that, each of the two dual-OTA-RC oscillators considered therein has three other equivalent forms having the same CE one of which employs both GCs. In [36], it was shown that from a given OTA-C oscillator, a new OTA-C oscillator structure, having exactly the same CE as the original circuit, can be derived using the operation of 'network transposition' [37] (see [38] for an interesting exposition of the concept of 'network transposition' in deriving adjoints of various multi-terminal modern active building blocks).

The object of this paper is to demonstrate that the nullor-based theory of op-amp-RC oscillator equivalencies presented earlier in [39, 40] is extendable to OTA-RC oscillators and that by doing so, a much larger number of equivalent OTA-RC oscillators having the same CE can be derived than possible with the theories presented in quoted works [33, 35, 37]. The methodology presented in this paper also leads to several other important consequences thereby considerably extending the utility of the generated additional OTA-RC oscillator equivalents.

2 Derivation of equivalent forms of OTA-RC oscillators: the nullor approach

OTAs could be differential input single-output (DISO)-type or differential input dual-output (complementary) (DIDO)-type. The nullor models for both are shown in Fig. 1 which is self-explanatory.

For the present purpose, we assume that, in the most general form, an OTA-RC oscillator can have a DIDO-type OTA. It may be mentioned that an implementation of a DIDO-type OTA can be obtained from the bipolar or CMOS architecture of a DISO-type OTA simply by addition of two pairs of complementary current mirrors to create the second current output terminal providing a current output complementary to the current output of the first output terminal. Furthermore, both types of OTAs are commercially available as off-the-shelf integrated circuits (ICs); for instance, LM3080/LM13600/LM13700 being the examples of DISO-type OTAs, whereas MAX 435 being an example of the DIDO-type OTA.

Consider now the following theorems:

Theorem 1 [39, 40]: Suppose there is a sinusoidal oscillator 'N' which employs $\boldsymbol{m}$ nullators, $\boldsymbol{m}$ norators and an arbitrary number of passive resistors and capacitors. If 'N' is transformed into another circuit 'N*' by interchanging all nullators and norators then 'N*' has the same CE as that of 'N'.

Theorem 2 [39]: Corresponding to any RC-nullor oscillator having $\boldsymbol{n}$ nodes (excluding the ground node which is taken 'external' to the circuit) and consisting of $\boldsymbol{m}$ nullors along with an arbitrary number of passive resistors and capacitors, there are $\boldsymbol{2n}$ grounded nullor-RC equivalent oscillator circuits having the same CE, with the set of $\boldsymbol{n}$ equivalent circuits obtained by choosing the ground node in $\boldsymbol{n}$ different ways and the remaining $\boldsymbol{n}$ equivalent circuits obtained by applying Theorem 1 on the preceding set.

In [39], the above theorems were shown to be useful artifices for generating equivalent op-amp-RC oscillators many of which were

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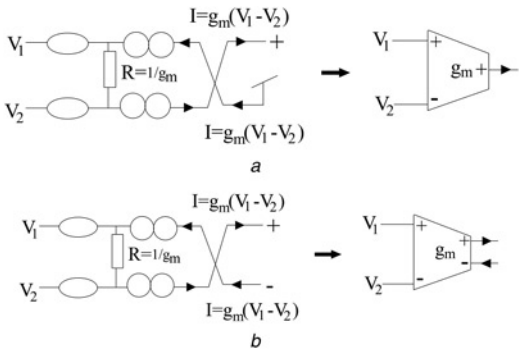


Fig. 1 *Nullor models of the OTAs*
a DISO-type OTA
b DIDO-type OTA

shown to possess interesting properties not present in the corresponding parent oscillator circuits. Although not demonstrated therein, it was envisaged in [39] that the theory could also be applied to oscillators using any other active building blocks which can be modelled by nullors. In view of this, it follows that since an OTA can be represented by a pair of nullors and a single resistor $R = 1/g_m$, the theory should also be applicable to OTA-RC oscillators of [22, 25, 33, 35] as well. In the following, we demonstrate that it is indeed so and the resulting equivalent OTA-RC oscillator structures exhibit many interesting properties not present in the chosen parent OTA-RC oscillators.

2.1 Case 1: derivation of equivalent forms of single-OTA-RC oscillators

A single-OTA-RC oscillator, in the general form can be shown as in Fig. 2*a* where '*N*' represents a 4-port RC circuit in which a DIDO-type OTA is embedded. Fig. 2*b* shows the nullor representation of such an oscillator.

Now applying Theorem 1 on the nullor circuit of Fig. 2*b*, we obtain an alternative oscillator having the same CE as in Fig. 2*c* from which the corresponding OTA-RC configuration having the same CE may be drawn as shown in Fig. 2*d*. It is interesting to note that the configuration of Fig. 2*d* is also derivable from that of Fig. 2*a* by applying the operation of 'network transposition' [36].

On each of the circuits of Figs. 2*a* and *d*, now we can apply Theorem 2. As per Theorem 2, from the circuit of Fig. 2*a* as well as that of Fig. 2*d*, four additional circuits can be generated by 'relocating' the ground terminal in each case thereby resulting in a family of ten single-OTA-RC oscillators having exactly the same

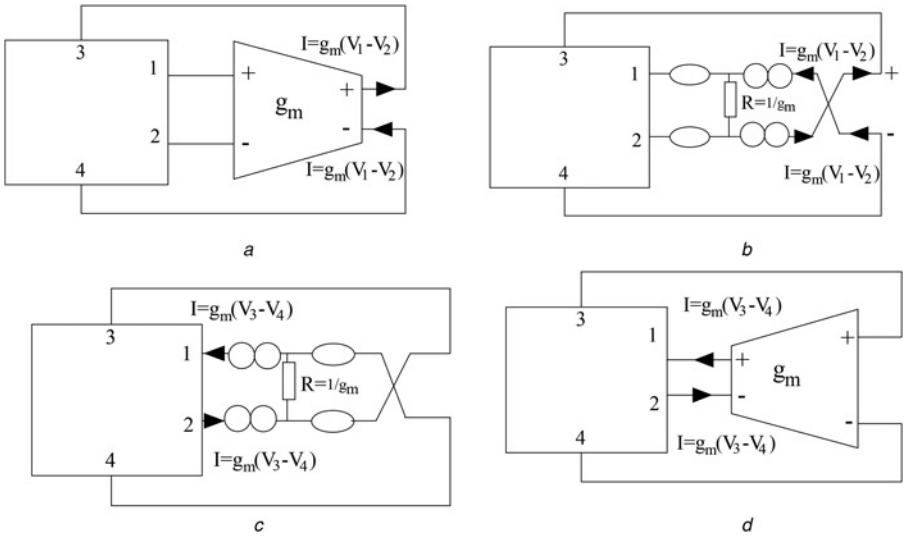


Fig. 2 *Nullor model of a single-OTA-RC oscillator and its transform according to Theorem 1*
a General form of a DIDO-OTA-based sinusoidal oscillator
b Nulor representation of the scheme of Fig. 2*a*
c An alternative oscillator having the same CE as the one in Fig. 2*a*
d OTA-RC configuration corresponding to the nullor model of Fig. 2*c*

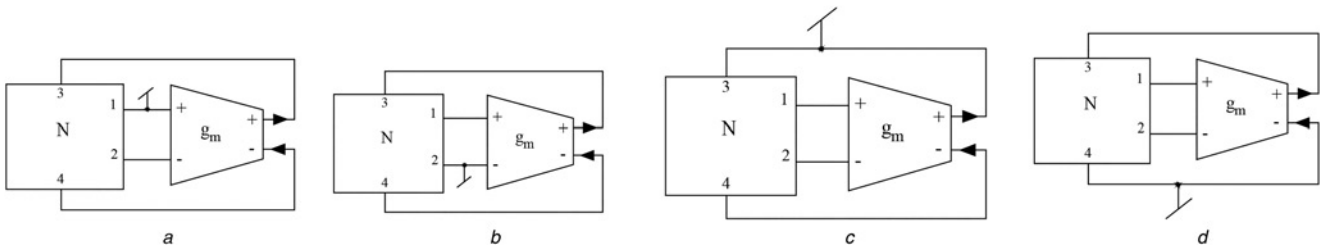


Fig. 3 *General representation of the four additional equivalent forms of a given single-OTA-RC oscillator based on the circuit of Fig. 2a*
a Equivalent oscillator with single-input OTA
b An alternative equivalent oscillator with single-input OTA
c Equivalent oscillator with a dual-input OTA
d An alternative equivalent oscillator with a dual input OTA

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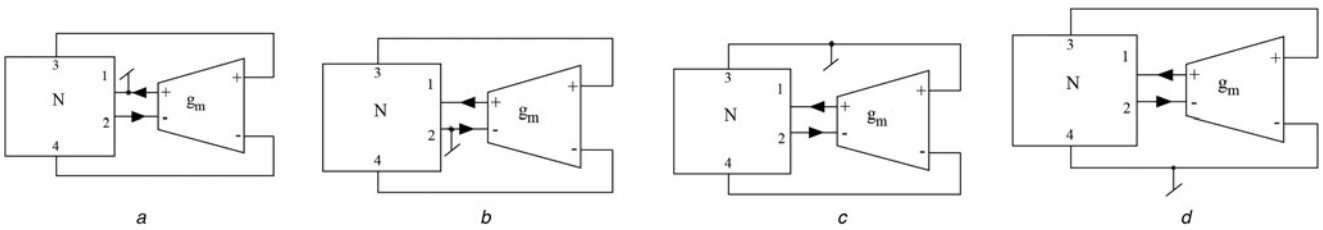


Fig. 4 *General representation of the remaining four additional equivalent forms of the same oscillator, but based on the model of Fig. 2d*
a Equivalent oscillator with single-output OTA
b An alternative equivalent oscillator with single-output OTA
c Equivalent oscillator with a single-input OTA
d An alternative equivalent oscillator with a single input OTA

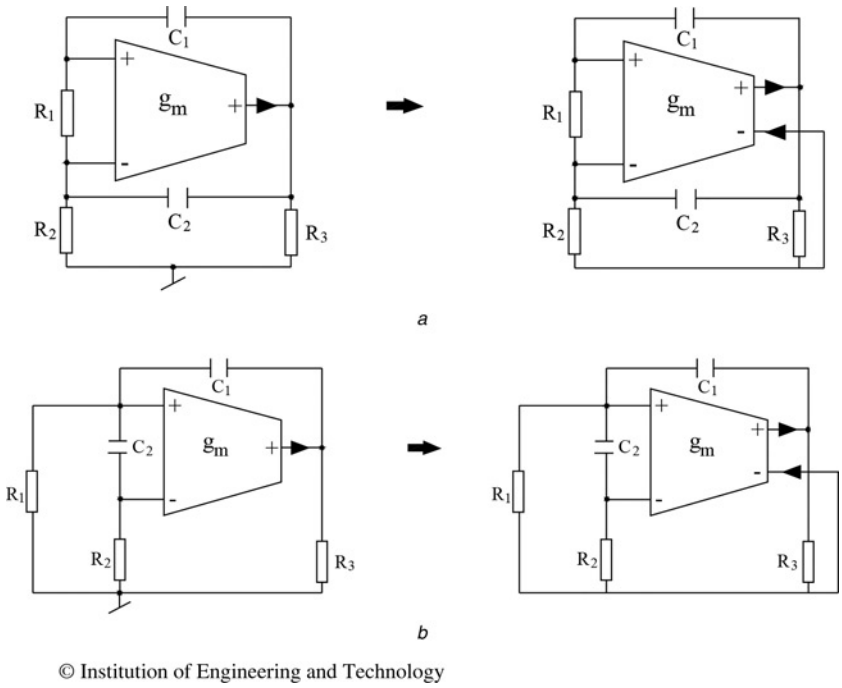


Fig. 5 *DIDO-OTA-RC oscillator circuits*
a Single-OTA-RC oscillator of Fig. 3*a* of [33] and its representation as a single DIDO-OTA-RC oscillator
b Single-OTA-RC oscillator of Fig. 4*a* of [33] and its representation as a single DIDO-OTA-RC oscillator

CE. These circuits are symbolically shown in Fig. 2*a*, *d*, Figs. 3*a–d* and 4*a–d*.

It is now interesting to note the following:

Note 1: In the circuits of Figs. 3*c*, *d*, and 4*a*, *b*, one of the output terminals of the DIDO-type OTA becomes redundant because of being grounded. Clearly, such circuits, therefore, can be realised practically by a normal DISO-type OTA as well, such as LM3080/LM13600/LM13700. However, it may be further noted that the oscillator circuits **d** of Fig. 3 and circuit **b** of Fig. 4 will in such a case be exactly same as those of Figs. 1*a* and *c* of [33]; whereas on the other hand, the circuit **c** of Fig. 3 and circuit **a** of Fig. 4 are analogous to those of Figs. 1*b* and *d* of [33], but will become exactly same if in both the cases (i.e. in the circuits of Figs. 3*c* and 4*a*) the polarities of the input terminals are reversed which will automatically result in the current going out of the output terminal which is the usual case in a DISO-type OTA.
Note 2: It may be observed that all the remaining four circuits, other than those of Figs. 3*c*, *d* and 4*a*, *b*, are entirely 'new'.

Consider now the two single-OTA-RC circuits depicted in Figs. 3*a* and 4*a* of [33] which are reproduced here (with permission), for convenience, in Figs. 5*a* and *b* which also show nullor models derived from these oscillators by replacing the DISO-type OTA by DIDO-OTA as shown in Figs. 5*c* and *d*, respectively (with ground node assumed external to the circuits).

Now, starting from the DIDO-OTA-RC oscillator circuits of Fig. 5*a* as well as Fig. 5*b*, by successive application of Theorems 1 and 2, ten single DIDO-OTA-RC oscillators as per the generic forms shown in Figs. 2*a*, *d*, 3 and 4 can be derived in each case (details omitted because of space limitations).
Note 3: Out of the ten derivable circuits corresponding to the circuit of Fig. 5*a*, the four circuits derived in [33] are found to be exactly the same as in [33] (subject to the compliance of the condition specified earlier in Note-1). However, there are six new oscillator circuits in this set which have not been known earlier.
Note 4: In a similar manner, using the present theory, a total of ten equivalent OTA-RC oscillators are derivable from the oscillator circuit of Fig. 4*a* of [33] (Fig. 5*b* herein) out of which there would be six new circuits (not shown here).

2.2 Case 2: derivation of equivalent forms of dual-OTA-RC oscillators

Using five theorems, three equivalent OTA-C oscillators having the same CE corresponding to each of the two oscillator circuit examples taken were derived in [35]. We now show that if we derive

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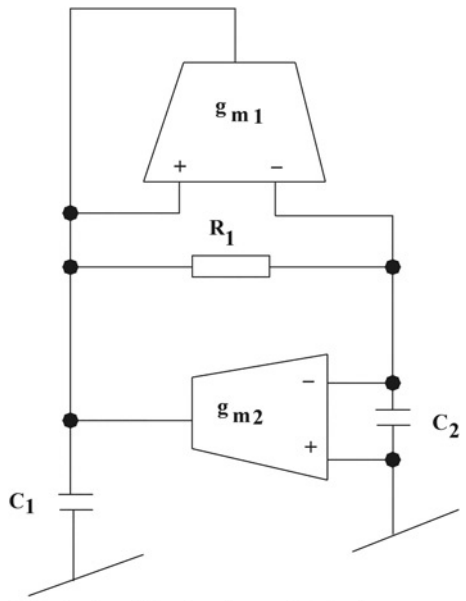


Fig. 6 *Dual-OTA-RC oscillator of example 1 of [35]*

equivalent forms of dual-OTA-RC oscillators from those exemplified in [35], by using the method presented here, we will obtain more equivalent oscillator circuits than those derived in [35].

By using Theorems 1 and 2, we first show that there are a total of eight equivalent oscillator circuits having the same CE corresponding to the oscillator circuit of example 1 of [35] (reproduced here, with permission, in Fig. 6).

The CE of this oscillator is given by

$$C_1C_2R_1s^2 + (C_1 + C_2 - g_{m1}C_2R_1)s + g_{m2} = 0 \qquad (1)$$

Note that in this oscillator, the condition of oscillation (CO) is controllable through g_{m1}, whereas frequency of oscillation (FO) can be independently controllable through g_{m2}.

The starting point of the required derivation is the configuration shown in Fig. 7*a* where the circuit of Fig. 6 has been redrawn with dual-output OTAs (instead of single-output OTAs) and the ground node has been considered external to the entire circuit. By applying Theorem 1 on this circuit, we obtain the corresponding circuit in Fig. 8*a*, (which can also be obtained by applying the operation of 'network transposition' [36] on the circuit of Fig. 7*a*). Now the generation of three additional circuits, that is, circuits of Figs. 7*b–d* from that of Fig. 7*a* and circuits of Figs. 8*b–d* from that of Fig. 8*a* are derivable by invoking Theorem 2 and choosing the ground node as nodes 3, 2 and 1, respectively, in each case. It may now be noted that the equivalent circuits of Figs. 7*b* and 8*c* are the same as derived in example 1 of [35] and Fig. 7*d* will become exactly same if polarities of the input terminals of both the OTAs are reversed, whereas the remaining five circuits, namely, those in Figs. 7*a*, *c*, and Fig. 8 'are entirely new'.

Consider now the oscillator circuit of example 4 of [35] (circuit of Fig. 8*a* of [35]) which is reproduced here, with permission, in Fig. 9.

This circuit has the CE

$$\begin{aligned}&(C_1C_2R_1R_2 + C_1C_2R_1R_3)s^2 \\ &+ \begin{pmatrix} C_1R_1 + C_2R_1 + C_2R_2 + C_2R_3 + g_{m2}C_1R_1R_3 \\ - g_{m1}C_2R_1R_2 - g_{m1}C_2R_1R_3 - g_{m2}C_2R_1R_2 \end{pmatrix}s \\ &+ (1 + g_{m2}R_3) = 0 \end{aligned} \qquad (2)$$

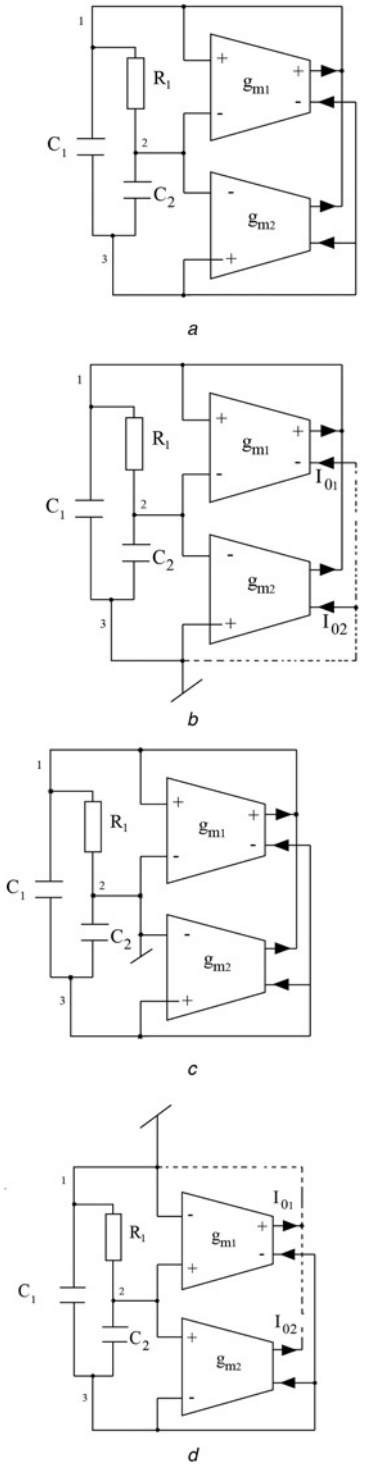


Fig. 7 *Four equivalent forms of the dual- OTA-RC oscillator of Fig. 3a of [35]*
a Equivalent oscillator with external ground
b Equivalent oscillator with node 3 grounded
c Equivalent oscillator with node 2 grounded
d Equivalent oscillator with node 1 grounded

with $C_1 = C_2 = C$, CO becomes independent of g_{m2} and can be adjusted by g_{m1}, whereas FO can be then controlled by g_{m2}.

When the proposed theory is applied to the circuit of Fig. 9, the number of equivalent circuits having the same CE [It may be pointed out that alternative methods of analysing OTA-RC oscillators to find their CE using nullator–norator representations have been described in [41–44].] as (2) have been found to be ten (however, to conserve space, these have not been shown here).

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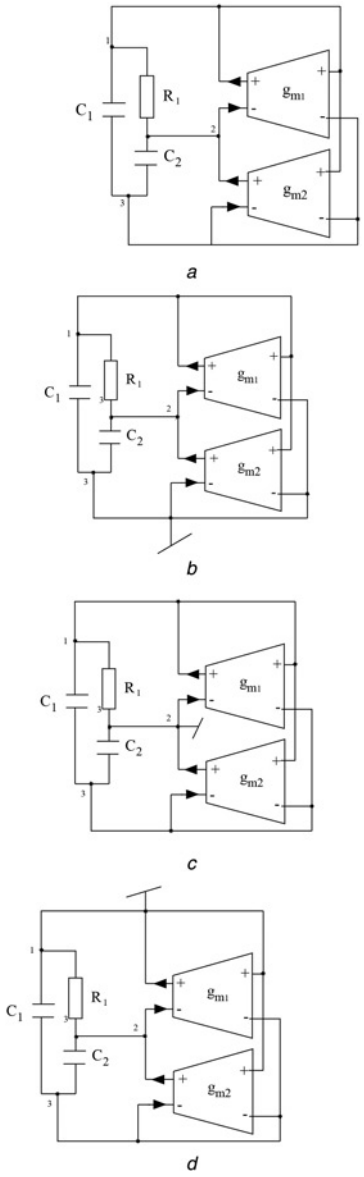


Fig. 8 *Remaining four equivalent forms of the dual-OTA-RC oscillator of Fig. 3a of [35]*
a Equivalent oscillator with external ground
b Equivalent oscillator with node 3 grounded
c Equivalent oscillator with node 2 grounded
d Equivalent oscillator with node 1 grounded

Note 5: It is worth pointing out that in this case also, only three equivalent circuits have been derived in [35] through the five theorems presented therein, whereas the application of the proposed theory yields seven additional entirely new equivalent circuits (although not shown here).

3 Interesting properties of generated equivalent OTA-RC oscillators

The following are now worth considering:

3.1 Generation of grounded-capacitor versions of the chosen OTA-C Oscillators

In the context of grounded-capacitors-based oscillators, as preferred for IC implementation [33–35, 39], it is interesting to note that, contrary to the disclosures of [33], there would result two 'both-GC' single-OTA-RC oscillators in the set of equivalent oscillators

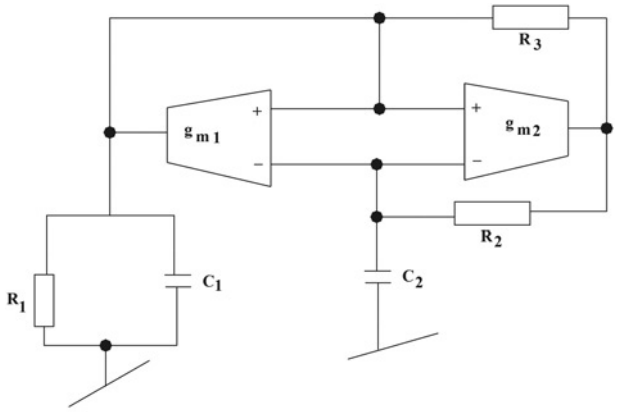


Fig. 9 *Dual-OTA-RC oscillator of example 4 of [35] (Fig. 8a therein)*

resulting from the application of the procedure explained in this paper on all single-OTA-RC oscillators considered in [33]. Similarly, there are two 'both-GC' oscillator equivalents as shown in Figs. 7*b* and 8*f* here in contrast to only a single 'both-GC' oscillator derivable from the theorems of [35] (see Fig. 3*a* therein).

3.2 Explicit-current-output single-OTA-RC and dual-OTA-RC oscillators

(i) In case of single-OTA-RC oscillators of Figs. 3*d*, *c* and 4*b* and *a*, one output terminal of the OTA is directly connected to ground. From an inspection of the circuits, it can be readily realised that this grounded output terminal can be readily ungrounded without altering the CE, and hence these single-OTA-RC oscillators are capable of providing an 'explicit current output from high output impedance nodes'. This is important in view of the fact that OTA oscillators providing explicit current outputs are the subject of considerable contemporary interest in the literature (for instance, see [30, 45]) because of their possible applications as signal generators for testing current-mode signal processing circuits.
(ii) In the class of two OTA-RC oscillators exemplified in this paper, those in Figs. 7*b*, *d* and 8*b*–*d* have one or two outputs directly connected to ground (one in case of the oscillators of Figs. 8*b* and *d*, and two in case of Figs. 7*b*, *d* and 8*c*). Owing to this, as explained above, in case of the oscillators of Figs. 7 and 8, those of Figs. 8*b* and *d* have one explicit current output available in each OTA (after ungrounding), whereas in case of the oscillators of Figs. 7*b*, *d* and 8*c*, two explicit current outputs are available (one each from each OTA).

3.3 Current-mode quadrature oscillators

It is further interesting to note that all those oscillators enumerated above in (ii) which have two explicit current outputs, that is, oscillators of Figs. 7*b* and *d* and those resulting from the application of the proposed theory on the circuit of Fig. 9, have the possibility of having the two available output currents in quadrature, thereby making these circuits suitable for quadrature outputs generation. A re-analysis of these circuits reveals that, indeed, this is true. It has been found that the two-OTA-RC oscillators of Figs. 7*b* and *d* both are characterised by

$$\frac{I_{o2}(s)}{I_{o1}(s)} = -\frac{g_{m2}}{R_1 g_{m1} s C_2} \tag{3}$$

without any condition, and thus these circuits are current-mode 'quadrature oscillators'. It must be pointed out that the set of ten

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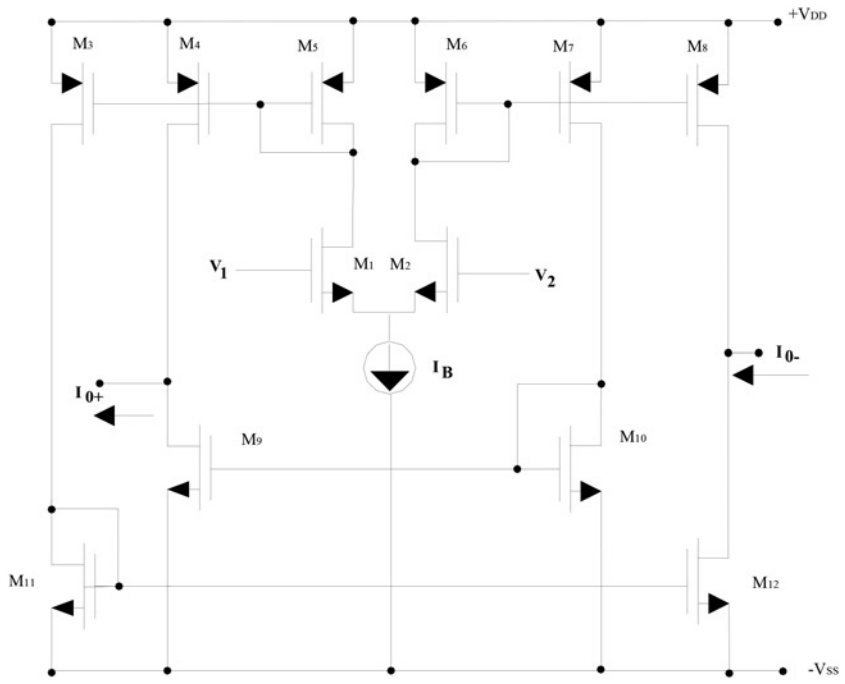


Fig. 10 *Multi-output OTA (MO-OTA)*

Table 1 Aspect ratios of the various MOSFETs

MOSFETs	W, μm	L, μm
M1, M2	5.76	0.72
M3, M4, M5, M6, M7, M8	2.16	0.72
M9, M10, M11, M12	1.44	0.72

equivalent OTA-RC oscillators derivable corresponding to the circuit of Fig. 9 also contain two quadrature oscillators (not shown here to conserve space); however, these circuits suffer from the requirements of equality of two capacitors and resistors for quadrature operation.

4 SPICE simulation results

To verify the workability of the OTA-RC oscillators derived in this paper, all the circuits were simulated in simulation program with integrated circuit emphasis (SPICE) using DIDO-type CMOS OTA [It may be pointed that the design of CMOS-OTAs can be improved by the techniques given in [46, 47].]

The aspect ratios of various metal–oxide semiconductor field effect transistors (MOSFETs) are given in Table 1 while the process parameters of 0.18 μm CMOS technology were employed in simulations.

The DC bias supply used was ±1.0 V and the DC bias current I_B was chosen appropriately in different cases. All the single-OTA-RC oscillators as well as all dual-OTA-RC oscillators described in this paper were simulated and were found to work as predicted by theory. However, to conserve space, we present the simulation results of current-mode quadrature oscillators of Fig. 7*b* only. The circuit was tested with $C_1 = C_2 = 10$ pf, $R_1 = 30$ KΩ, $I_{B1} = 8.4$ μA and $I_{B2} = 35$ μA which resulted in oscillation frequency of 1.2 MHz exhibiting the total harmonic distortion of 0.8%.

Fig. 11 shows the waveforms obtained from the circuits of Fig. 7*b*. The measured value of the phase shift between the two waveforms has been found to be 88.916°. Thus, the waveforms are 'almost' in quadrature, with the error in the phase difference being merely 1.2%.

The SPICE simulation results, therefore, have confirmed the workability of new equivalent OTA-RC oscillators generated by the theory presented in this paper.

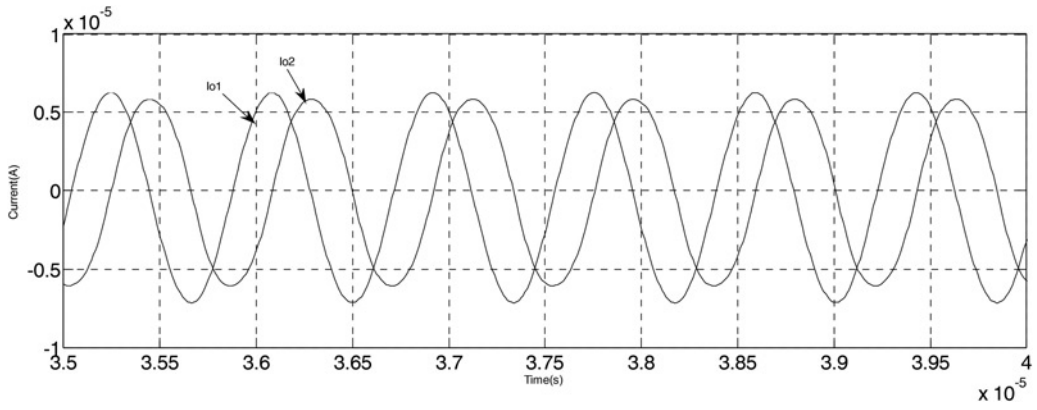


Fig. 11 *SPICE generated waveforms for the oscillator of Fig. 7b*

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5 Concluding remarks

It has been demonstrated that the theory of deriving op-amp-RC equivalent oscillator structures using the nullor formalism can be extended OTA-RC oscillators as well and that it is more general than that presented in [33, 35] (through a number of theorems presented therein). This has been confirmed by demonstrating the following:

(a) The presented nullor-based theory shows the existence of ten equivalent forms for each of the two single-OTA-RC oscillators considered in [33] for which only four equivalents have been derived therein.
(b) When applied to the dual-OTA-RC oscillators of [35], eight to ten equivalent forms of the dual-OTA-RC oscillators are derivable as against only three equivalent OTA-C oscillators corresponding to each of the two circuits derived through five theorems in [35].

Some additional features of the circuits resulting from the presented theory are:

(i) The theory presented in this paper shows that, in contrast to what has been demonstrated in [33, 35], corresponding to a given OTA-RC oscillator, there are 'two equivalents' (having the same CE) that employ 'both GC's rather than only one, as shown in [33, 35]'.
(ii) In case of single-OTA-RC oscillators of Figs. 3 and 4, some of the single-OTA-RC oscillators are capable of providing an explicit current output at high output impedance nodes. This is important in view of the fact that OTA oscillators providing explicit current outputs are the subject of considerable contemporary interest in the literature, for instance, see [30, 45] because of their possible applications as signal generators in current-mode signal processing circuits.
(iii) In the class of two OTA-RC oscillators discussed in this paper, some of those shown in Figs. 7 and 8 have one or two outputs that are connected directly to ground (**one** in case of the oscillators of Figs. 8*f* and *h*, and **two** in case of Figs. 7*b*, *d* and 8*g*). Owing to this, as explained above, in case of the oscillators of Figs. 7 and 8, a number of circuits are capable of providing explicit current outputs.
(iv) It is further interesting to note that among all oscillators enumerated above in (iii) which have two explicit current outputs, oscillators of Figs. 7*b* and *d* have the two available output currents in quadrature.

It is worth mentioning that the disclosure of these interesting properties has been possible because the presented unified theory of deriving equivalent structures starting from OTA-RC oscillator models is based on differential input and complementary dual-output-type OTAs rather than single-output OTAs. This aspect of OTA-RC oscillators does not appear to have been dealt with in the earlier literature.

From the results presented in this paper, it may, therefore, be inferred that the nullor-based theory for deriving equivalent OTA-RC sinusoidal oscillators, as presented in this paper (which also embodies the 'network transposition' or adjoint 'transformation' of [36]), is more general than the methods of deriving equivalent OTA-RC oscillators presented in [33, 35] since it produces not only more equivalents, but also generates a number of new topologies having practically useful properties which have not been available in the chosen parent OTA-RC oscillator(s).

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