Analysis and Design of LC Oscillators using Composite Current Conveyors

Ivailo Pandiev[1]

Abstract – **In this paper new sinusoidal LC oscillators using a single composite current conveyor and grounded LC elements are presented. The proposed circuits provide the following advantages: (1) the insignificant influence of the load over the parameters of the oscillators, (2) ability for independent fine tuning of both oscillation frequency and oscillation condition by grounded capacitor (or inductor) and resistor, (3) low output resistance, (4) minimum number of external passive elements (two resistors and a LC tank). Some recommendations for designing this kind of analogue circuits are given based on simulation modelling and symbol analysis of the characteristic equations. Experimental results that confirm the theoretical analysis are given.**

Keywords – **Circuit theory and design, LC oscillators, Current conveyors, Current amplifiers.**

I. INTRODUCTION

The sinusoidal LC oscillators have been found useful in many applications, such as communications, control systems, analog signal processing and measurement systems. In the past two decades several current conveyor-based RC sinusoidal oscillators [1-7] and current-feedback amplifier (CFA) based RC (or LC) oscillators [8-12] are proposed in the literature. Each of the oscillator circuits of [1-7] uses one, (two or three) second-generation current-conveyors (CCII) and a small number of resistors and capacitors. In most cases the resistors and capacitors are connected to ground. Only the circuits presented in Ref. [1] and [4] use one floating resistor or capacitor. In fact, the grounded resistors allow simple and independent control of the frequency and condition of oscillation. When grounded resistor for control of the oscillation frequency is replaced by a JFET or CMOS digital potentiometer, voltage-controlled or digitally-controlled oscillators can be realized. The CFA-based oscillators in comparison with the current conveyor circuits have small output impedance and larger bandwidth. However, the majority of published RC (LC) oscillators usually generate sinusoidal signal with frequency up to 1*MHz*, as well as the load, connected to the output, can have significant influence on the oscillation condition and frequency stability of the output signal. The oscillator circuit given in Ref. [12] consists of a single CFA and several passive RLC elements. A parallel resonance LC tank was connected to the additional op amp correction pin of the CFA. This additional pin is connected between the first stage (current-controlled source) and the second stage (voltage follower), where the resistance is very high (magnitude of several mega ohms). The control of the oscillation condition is fulfilled by two feedbacks - one negative, realized with the resistors R_1 – R_2 and the capacitor C_1, compensating the phase distortions in the closed loop, and one positive, realized with the resistors R_3 and R_4. The main drawbacks of this circuit are the comparatively difficult tuning of the oscillation condition and the insufficient frequency stability, because the Q-factor is dependent on the resistor R_2 's value. The resistor R_2 is used to set the bandwidth (at –3dB) of the CFA and to form the voltage gain with the resistor R_1.

This paper proposes two new LC oscillators using a single current conveyor with an additional output voltage follower and a small group of passive RLC elements. The oscillation condition and frequency of the created circuits can be controlled through a single grounded resistor and grounded capacitor (or inductor) respectively. The proposed LC oscillators are obtained from the classical Colpitts and Hartley circuits, realized with discrete transistors [13]. In fact, the presented circuits are improvement variants of the LC oscillators given in Ref. [12]. Experimental results for the new LC oscillators, which confirm the theoretical analysis, are given.

II. COMPOSITE CURRENT CONVEYORS

The current conveyors (current-controlled amplifiers) are a special type of op amps and can be obtained by CFAs, if the output buffer is removed. The current conveyors can be viewed as *ideal transistors*. Like transistors, they have three terminals – a high impedance input (*B - base*), a low-impedance input/output (*E - emitter*), and the current output (*C - collector*). The op amps AD844 (from Analog Dev.), OPA860, OPA615 (from Texas I.) and MAX436 (from Maxim) are typical representatives of the current conveyors.

The composite current conveyor is a cascade structure of positive second-generation current conveyor (CCII+) and an additional voltage follower, similar to the CFAs. The input terminal of the voltage follower is connected to the *C* terminal of the CCII+. The *C* terminal is presented as an external pin of the op amp. The schematic representation of a composite current conveyor can be as an op amp or as a bipolar transistor, as shown in Fig. 1a and Fig. 1b [13]. Its linear model, presented in Fig. 1c, reflects the small-signal behavior of the real device. The model includes the following elements: input and output buffers (voltage followers); i_e – controlled current source; r_b and C_b – input resistance and capacitance of the non-inverting input; r_e – resistance of the inverting input ; r_c and C_c – output resistance and capacitance.

For this composite current conveyor the general relation between input and output voltages and currents can be given by the following hybrid matrix

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$$\begin{bmatrix} i_B \\ u_E \\ i_C \\ u_o \end{bmatrix} = \begin{bmatrix} 1/Z_b & 0 & 0 \\ 1 & 1/r_e & 0 \\ 0 & 1 & 1/Z_c \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_B \\ i_E \\ u_C \end{bmatrix}, \qquad (1)$$

where $Z_b = r_b \parallel (1/pC_b)$ and $Z_c = r_c \parallel (1/pC_c)$.

The matrix representation given with Eq. (1) is valid only for the ideal input and output voltage followers.

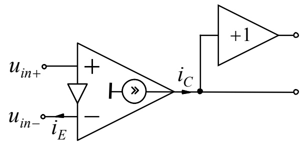

Fig. 1a. Symbol of a composite current conveyor as an op amp

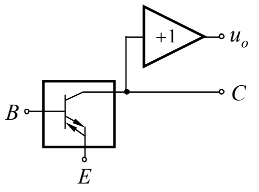

Fig. 1b. Symbol of a composite current conveyor as a bipolar transistor

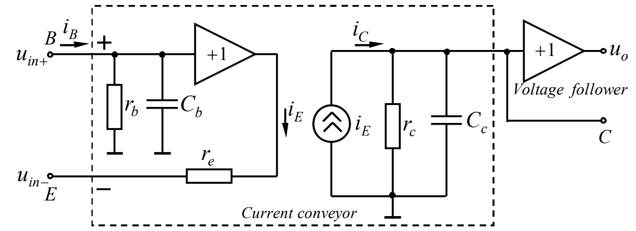

Fig. 1c. Linear model of the composite current conveyor

III. CIRCUITS DESCRIPTION

The proposed circuits of the sinusoidal LC oscillators are shown in Fig. 2a and Fig. 2b.

The LC oscillator, presented in Fig. 2a (LCO1), is based on a composite current conveyor. The positive capacitive feedback is implemented with a parallel LC resonant circuit (LC tank). The voltage in the common node of the capacitors C_1 and C_2 is applied to the B terminal of the current conveyor. The grounded inductor L_3 of the LC tank is connected to the common node of the C_1 and R_C. The L_3 can be replaced with a variable RF inductor for tuning the oscillation frequency. The capacitors (C_1 and C_2) and the inductor L_3 of the LC tank are not ideal. The active resistance r_{L3} and the capacitance C_{L3} of the inductor L_3 determine the losses. The parasitic inductances and leakage currents of the SMDs C_1 and C_2 are small and can be neglected.

The small resistor R_C, connected between the C terminal of the current conveyor and the LC tank, is used to keep the current conveyor in a linear mode of operation when the oscillation condition is fulfilled. The negative feedback of the circuit is implemented with the grounded resistor R_E. This resistor can be a trimmer-potentiometer, used for tuning the negative feedback depth until the oscillation condition is fulfilled and desired amplitude of the output signal is obtained. When the oscillation condition is fulfilled, the oscillator is generating sinusoidal signal with a frequency equal to the resonant frequency of the LC tank.

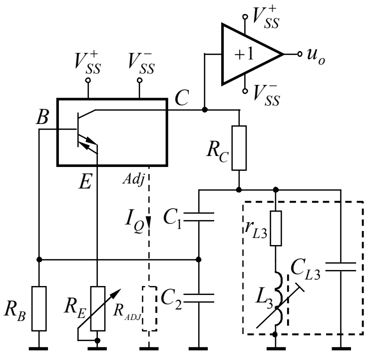

Fig. 2a. Proposed capacitive feedback LC oscillator (LCO1) using composite current conveyor

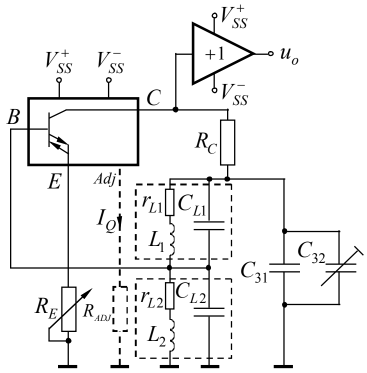

Fig. 2b. Proposed inductive feedback LC oscillator (LCO2) using composite current conveyor

The DC current component i_B of the current conveyor is flowing through the grounded resistor R_B. The resistor R_B value has to be chosen larger than the resonant frequency of the LC tank ($R_B = (5 \div 10)R_{re}$). The output signal u_o of this circuit is obtained at the end of the voltage follower. In some of the monolithic current conveyors there quiescent current is set with an external resistor R_{ADJ}, connected between pins *Adj* and V_{SS}^- (or ground). The resistor R_{ADJ} adjusts the transconductance of the current conveyor ($S = 1/r_e$) and allows to optimize the bandwidth and the voltage amplification.

Using the hybrid matrix given in Eq. (1), which characterizes the composite current conveyor by routine analysis of the LCO1, the characteristic equation is found:

$$p^2 C_1^{'} C_2^{'} L_3 (R_E + r_e) + p[(C_1^{'} + C_2^{'}) L_3 \frac{R_E + r_e}{R_{oe}} - C_1^{'} L_3] +$$

$$+ (C_1^{'} + C_2^{'})(R_E + r_e) = 0, \qquad (2)$$

where $R_{oe} \approx (R_{re} + R_C)(r_c \parallel r_b)$ is the equivalent resonance resistance of the circuit, $R_{re} = \rho^2 / r_{L3}$ is the equivalent resonance resistance of the LC tank, $\rho = \sqrt{L_3 / C_{12}}$ is the characteristic resistance of the LC tank, $C_{12} = C_1^{'} \parallel C_2^{'}$, $C_1^{'} = C_1 + 2C_c + 2C_{L3}$ and $C_2^{'} = C_2 + 2(C_c + C_{L3}) + C_b$.

The oscillation condition and oscillation frequency are given by

$$\underbrace{\frac{C_1'}{C_1'+C_2'}}_{\beta^+}=\underbrace{\frac{R_E+r_e}{R_{oe}}}_{A_U^{-1}} \qquad (3)$$

and $$\omega_o=1/\sqrt{L_3C_{12}}\,. \qquad (4)$$

respectively. Thus, R_E appears only in the expression for oscillation condition and L_3 appears only in the equation for oscillation frequency. Therefore, each one of them can be independently controlled through the grounded resistor R_E and the grounded inductor L_3, respectively.

The passive sensitivities of the LCO1 are low and obtained as

$$S_{C_1'}^{\omega_o}=-\frac{1}{2}\frac{C_2'}{C_1'+C_2'}\,;\; S_{C_2'}^{\omega_o}=-\frac{1}{2}\frac{C_1'}{C_1'+C_2'}\,;\; S_{L_3}^{\omega_o}=-0{,}5\,.$$

The second LC oscillator (LCO2), based on a composite current conveyor with positive inductive feedback, is shown in Fig. 2b. In this circuit, the voltage in the common node of the L_1 and L_2 is applied to the *B* terminal of the current conveyor. The capacitor $C_3=C_{31}+C_{32}$ of the LC tank is presented in a parallel configuration by the C_{31} and C_{32}. The variable capacitor C_{32} is used for tuning the oscillation frequency. The characteristic equation for the LCO2 can be given as

$$p^2[L_1L_2C_3'(R_E+r_e)+L_1^2C_3'(R_E+r_e)]+p[L_1^2\frac{R_E+r_e}{R_{oe}}+$$

$$L_1L_2\frac{R_E+r_e}{R_{oe}}-L_1L_2]+L_1(R_E+r_e)=0\,, \qquad (5)$$

where $C_3'=C_3+C_c+C_{L1}\parallel C_{L2}$ and $R_{re}=\rho^2/(r_{L1}+r_{L2})$.

The oscillation condition and frequency can be obtained as

$$\underbrace{\frac{L_2}{L_1+L_2}}_{\beta^+}=\underbrace{\frac{R_E+r_e}{R_{oe}}}_{A_U^{-1}} \qquad (6)$$

and $$\omega_o=1/\sqrt{\underbrace{(L_1+L_2)}_{L_{12}}C_3'}\,. \qquad (7)$$

The oscillation condition for the LCO2 can be adjusted by the grounded resistor R_E. The oscillation frequency can be independently adjusted by a grounded capacitor C_{32}. The passive sensitivities are low and can be obtained as

$$S_{L_1}^{\omega_o}=-0{,}5L_1/L_{12}\,;\; S_{L_2}^{\omega_o}=-0{,}5L_2/L_{12}\,;\; S_{C_3'}^{\omega_o}=-0{,}5\,.$$

IV. DESIGN PROCEDURE

The above analytical formulas, as a result of the theoretical analysis, are the base of the design procedure for the proposed LC oscillators. The circuit elements are calculated using predefined oscillation frequency f_o, f_o - sensitivities, amplitude of the output signal for a given load resistance R_L and *THD*. The schematic design for the proposed circuits is based on the following sequence:

- The circuit LCO1 (Fig. 2a) or LCO2 (Fig. 2b) is selected. The LCO1 is with a capacitive feedback and the f_o is controlled by a grounded inductor. The LCO2 is with inductive feedback and the f_o is tuned by a grounded capacitor.
- The current conveyor with output buffer is selected according to the following conditions: bandwidth – 3dB $BW_{0,7}>(2\div 5)f_o$; input and output resistance, so that for selected LC elements to accomplish the conditions $r_b>>R_{re}$ and $r_c>>R_{re}$; supply voltage $|V_{ss}|\geq(1{,}2\div 2)U_{om}$ and load resistance $R_L\geq R_{L,\min}$ ($R_{L,\min}$ is the minimum permitted load resistance, connected to the output of the buffer).
- The voltage amplification $A_{U,\min}$ of the op amp is chosen, according to the given oscillation frequency.
- The inductance of the inductors L_3 for LCO1 or L_{12} for LCO2 is selected. The following empirical values for the inductance can be recommended according to the oscillation frequency: $L\geq 100\mu H$ for f_o within $100kHz\div 1MHz$; $L=10\div 100\mu H$ for $1\leq f_o\leq 10MHz$; $L\leq 10\mu H$ for $f_o\geq 10MHz$.
- The values of the elements, forming the coil serial-parallel equivalent circuit (r_L, C_L and L), are determined empirically.
- The capacitances C_{12} for LCO1 or C_3 for LCO2 are calculated, according the Eq. (4) and Eq. (7), respectively.
- The capacitances C_1 and C_2 for LCO1 are calculated $C_1=C_{12}/(1-\beta^+)-2(C_c+C_{L3})$ and $C_2=C_{12}/\beta^+-$ $-2C_c-C_b-2C_{L3}$, where $\beta^+=1/A_{U,\min}$.
- The inductances L_1 and L_2 for LCO2 are calculated $L_1=L_{12}(1-\beta^+)$ and $L_2=\beta^+L_{12}$, where $\beta^+=1/A_{U,\min}$.
- The characteristic resistance and the equivalent resistance of the LC oscillator are calculated.
- The R_E is found by the Eq. (3) and Eq. (6), respectively.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

To verify the theoretical analysis, the proposed LC oscillators, shown in Fig. 2a and Fig. 2b, were implemented using a monolithic composite current conveyor OPA860 (from Texas Instruments), biased with $\pm 5V$ supplies. The values of the passive components are: $R_C=50\Omega$, $R_B=100k\Omega$ (for the LCO1), $R_{ADJ}=250\Omega$ (sets approximately $I_Q=11{,}2mA$ and $r_c=54k\Omega$, $C_c=2pF$, $r_b=455k\Omega$, $C_b=2{,}1pF$ and $r_e=8\Omega$) and R_E varies from 1 to $50k\Omega$. In both cases, oscillators are started by tuning the resistor R_E. The limit cycle stability is guaranteed by the nonlinear internal mechanism of the used current amplifiers.

TABLE I
EXPERIMENTAL RESULTS OF LCO1 FOR VARIOUS FREQUENCIES

Design f_o [MHz]	**0,1**	**1**	**10**	**20**	**50**	**100**
$C_1^{'(1)}$ [pF]	5,07nF	507	50,7	27	20,3	5,07
$C_2^{'(1)}$ [pF]	5,07nF	507	50,7	27	20,3	5,07
C_{12} [pF]	2,53nF	253	25,3	13,48	10,15	2,53
L_3 [μH]	1mH	100	10	4,7	1	1
r_{L3} [Ω]	12	6,5	2,1	1.8	1,2	2,5
ρ [Ω]	629	629	629	590	313	629
R_{oe} [kΩ]	19,58	26,91	27,75	27,86	23,27	27
Measured f_o [MHz]	**0,1**	**1,001**	**10,01**	**20,01**	**50**	**100**
THD [%]	**0,21**	**0,25**	**0,32**	**0,4**	**0,5**	**0,85**

Note: (1) $C_{L3} < 1pF$ is neglected.

TABLE II
EXPERIMENTAL RESULTS OF LCO2 FOR VARIOUS FREQUENCIES

Design f_o [MHz]	**0,1**	**1**	**10**	**20**	**50**	**100**
L_1 [μH]	1mH	47	4,7	1,5	1	0,57
L_2 [μH]	1mH	47	4,7	1,5	1	0,57
$L_1 + L_2$ [μH]	2mH	94	9,4	3	2	1,15
$C_3^{'(2)}$ [pF]	1260	270	27	21,1	5,07	2,2
$r_{L1} + r_{L2}$ [Ω]	24	13	2,2	3,6	2,4	5
ρ [Ω]	1260	590	590	376	628	723
R_{oe} [kΩ]	29,7	17,9	40,3	22,7	40,7	35,6
Measured f_o [MHz]	**0,1**	**1,01**	**10,1**	**19,9**	**50,1**	**99,8**
THD [%]	**0,2**	**0,24**	**0,36**	**0,42**	**0,51**	**0,92**

Note: (2) $C_{L1} \| C_{L2} < 1pF$ is neglected.

The experimental results of the proposed LC oscillators are presented in Table 1 and Table 2. Table 1 and 2 show the oscillation frequency and *THD* within the range 0,1 – 100*MHz* against the LC tank values. The coefficient of the positive feedback β^+ are chosen 0,5 for all of the design frequencies, which guarantee the maximal bandwidth of the current op amp ($A_{U,\min} \geq 1/\beta^+$ or $A_{U,\min} \geq 2$, where for the op amp OPA860 the bandwidth $B_{0,7} = 470MHz$ is significantly larger than the chosen maximum oscillation frequency equal to 100*MHz*). Using calculations according to the proposed design procedure, the parameters of the LC tank given in Table 1 and 2 have been determined. The quality characteristics of the inductors are obtained experimentally using Spectrum/ Impedance Analyzer HP4195A.

The amplitude of the output signal $u_{o,m} = 8V$ (peak to peak) at $R_L = 500\Omega$, the DC voltage component $u_{o,DC} < 1mV$ and the $THD < 1\%$ were obtained throughout the whole frequency range (0,1 – 100*MHz*).

VI. CONCLUSION

In this paper two new sinusoidal LC oscillators using a single composite current conveyor with grounded LC tank have been presented. Their oscillation frequency and oscillation condition can be independently controlled by a grounded capacitor (or inductor) and a grounded resistor, respectively. The circuits described are simpler and do not have some of the drawbacks, encountered in previously reported circuits, based on CCII+ and CFAs. The proposed oscillators have been tested with a monolithic composite current conveyor, obtaining good behavior for low and high frequencies.

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