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Voltage Controlled Integrator and Linear Quadrature-VCO Using MMCC

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Abstract

A Voltage Controlled Oscillator (VCO) based on the new multiplication-mode current conveyor (MMCC) building block is presented. The oscillator is realized using a double integrator loop (DIL) where a linear frequency (f_o) versus the control voltage (V_c) tuning characteristics with quadrature sinusoid signal generation in a range of 40 kHz ≤ f_o ≤ 700 kHz had been experimentally verified. The f_o— sensitivity is low while the frequency stability factor (S_f >>1) is high at satisfactory values of total harmonic distortion (THD ≈ 1.11%).

Keywords: *MMCC, quadrature oscillator, linear VCO, current conveyor*

1. Introduction

Recently a new active building block, viz., the MMCC [1] is introduced; the element is quite attractive for analog signal processing and wave generation applications. It is essentially an elegant current conveyor element with unity current gain [2] wherein the voltage at the current injection x-node is the product of a control voltage (V_c) and an input excitation voltage signal. The signal V_c , after being scaled by a multiplication factor k (volt $^{-1}$) is copied at the current source input x-node of the device. We propose here the implementation of the MMCC block with readily available IC devices, viz. the four quadrant multiplier (ICL-8013 or HA-2556) [3] followed by a current feedback amplifier (AD-844) CFA element [4]. The CFA is a unity current-gain amplifier with several advantages cited in the literature [5-7].

The ICL-8013 (or HA2556) is a four quadrant analog multiplier whose output is proportional to the algebraic product of two input signals with a scale factor k (usually 0.1 ≤ k ≤ 0.5) in volt^{-1}. The features of high accuracy (≈1%), relatively wide bandwidth (BW ≈ 1MHz) and enhanced versatility make it suitable for various applications in electronically tunable signal processing and wave generation [3-8].

We present here the design of a MMCC based DIL sinusoid oscillator (involving one non-inverting and the other inverting type). The feature of four quadrant operation of the multiplier device is utilized here for realizing the opposite polarity ideal integrators by using a bipolar d.c. control voltage (±V_c). A linear f_o -tuning law in a range of 40 kHz ≤ f_o ≤ 700 kHz with satisfactory quadrature signal generation had been measured both by PSPICE macromodel simulation [9] and with hardware circuit implementation. Analysis on the effects of device port mismatch errors (ε) indicate that f_o is practically active insensitive and the effects of the shunt parasitic components of the CFA-device are negligible. The frequency stability factor of the proposed oscillator is quite high (S_f >>1) at low values of measured THD (≈ 1.1 %). The aspect of electronic tunability, along with the capability of quadrature sinusoid signal generation is an attractive property of such an oscillator in view of its various applicabilities in signal processing for communuication and instrumentation fields. A comprehensive listing of the allied bibliography is presented in a tabular form which clearly indicates several superior features of the proposed design compared to the previous work.

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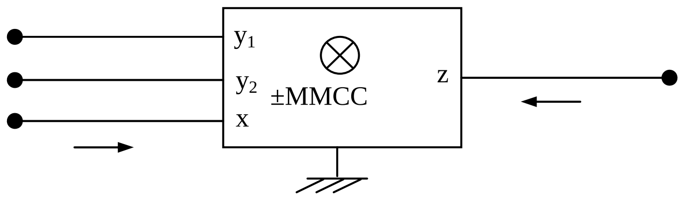
2. Research Method

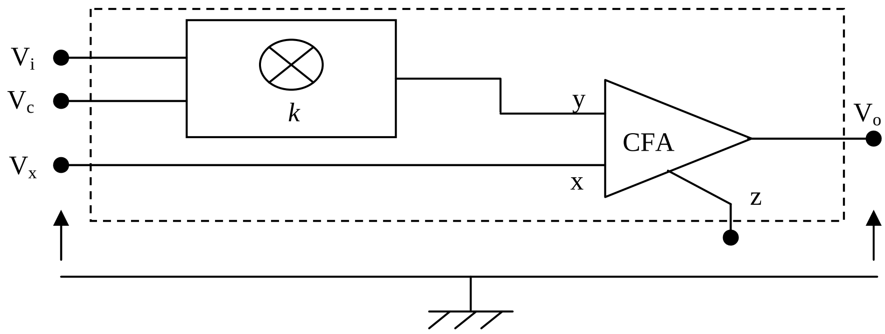
The circuit symbol of the MMCC is shown in Figure 1(a) where the nodal relations are $I_z=I_x$, $V_x=kV_{y1}V_{y2}$ and $I_{y1}= 0=I_{y2}$. The IC chip level implementation of the block is shown in Fig. 1(b); here the nodal relations of the multiplier element is $V_y=kV_{y1}V_{y2}$ and those of the CFA [4] are $V_x=V_y$, $I_z=I_x$, $I_y=0$ and $V_o=V_z$. Combining these relations we get the terminal characteristics of the MMMC where in Fig. 1(b), V_c and V_i may be regarded as the control voltage and the input voltage respectively. Additionally, one gets a voltage source output at V_o, which is not usually configurable in the conventional current conveyor [2]. The MMCC based integrators are shown in Figure 2(a) and (b); a bipolar control voltage ($\pm V_c$), amenable to the four quadrant multiplier, may be used to realize the non-inverting / inverting type ideal integrators in Figure 2 with T as the time constant, given by transfer (F)

$$F \equiv V_o/V_i = \pm 1/sT \quad ; \quad T = RC/kV_c. \tag{1}$$

The alternate realization in Figure 2(b) uses a positive V_c to get an inverting integrator. Design of the DIL with this structure, along with the other non-inverting structure here with $+V_c$, could provide a single control voltage terminal–an advantageous feature for microcircuit adaptation of the proposed linear VCO.



(a) Circuit symbol of MMCC



(b) MMCC implementation using multiplier (ICL 8013/HA 2556) and CFA (AD-844)

Figure 1. The Multiplication Mode Current Conveyor (MMCC)

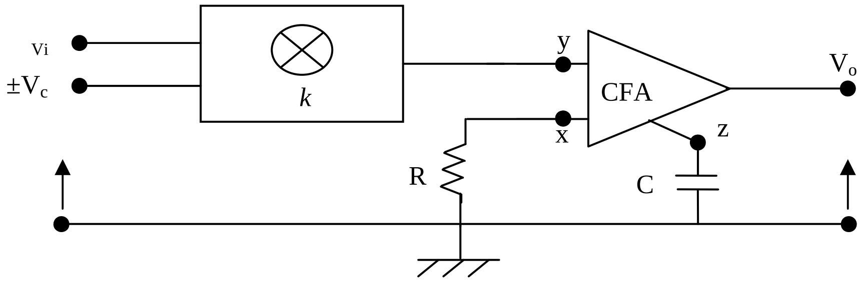
The characteristic equation of the oscillator, as in Figure 2(c), is:

$$1 + s^2 T_1 T_2 = 0 \quad ; \quad T_{1,2} = (R_{1,2} \; C_{1,2})/ \; kV_c. \tag{2}$$

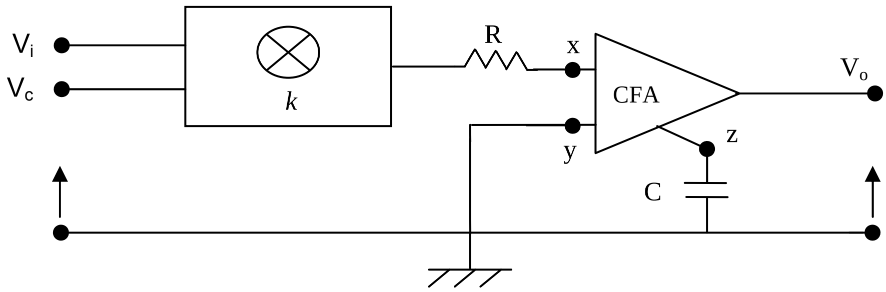
The oscillation frequency is:

$$\omega_o = kV_c / \sqrt{(T_1T_2)} \tag{3}$$

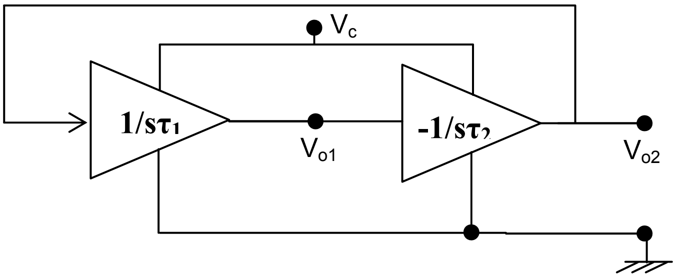
Since the loop consists of ideal integrators, no realizability condition is needed; hence no component matching constraint leading to minimized passive-sensitivity. The generated signal frequency (f_o) thus is linearly tunable with V_c while a suitable band may be selected by appropriate choice of the RC products; signals V_{o1} and V_{o2} have quadrature phase property since $V_{o1}(\omega)=V_{o2}(\omega) / j\,\omega\,\tau_1$



(a) Either polarity integrator design with ± V_c



(b) Alternate inverting integrator with +V_c



(c) Double integrator loop sinusoid quadrature-signal output (V_{o1} & V_{o2}) oscillator

Figure 2. Ideal Integrators Using MMCC

2.1. Non-ideal Effects

The device imperfections may be expressed in terms of non unity port transfer ratios [6], [10-11] as $I_z=a\,I_x$, $V_x=b\,V_y$ and $V_o=\delta\,V_z$. These ratios may be postulated as $a = 1-\boldsymbol{\varepsilon_i}$, $b=1-\boldsymbol{\varepsilon_v}$ and $\delta=1-\boldsymbol{\varepsilon_o}$ where the error ($|\boldsymbol{\varepsilon}| << 1$) quantities [6, 11] are quite low in magnitude. We may also express the multiplication scale factor as k (volt^{-1}) = $(1 - \boldsymbol{\varepsilon_m})$ such that the quantity (kV_c) may be considered as a dimensionless error factor of $\boldsymbol{\varepsilon_m}$.

Assuming finite nonzero errors ($\boldsymbol{\varepsilon} \neq 0$), we get the modified values as:

$$\tau'/\tau = (1 - \boldsymbol{\varepsilon_t}) \quad (4)$$

and,

$$\omega_o'/\omega_o = \sqrt{(1 - \boldsymbol{\varepsilon_T})} \quad (5)$$

Where,

$$\boldsymbol{\varepsilon_t = \varepsilon_i + \varepsilon_v + \varepsilon_o + \varepsilon_m} \text{ and } \boldsymbol{\varepsilon_T = \varepsilon_{t1} + \varepsilon_{t2}} \quad (6)$$

$\boldsymbol{\varepsilon_{t\,1,2}}$ denote deviation factors corresponding to the two integrator time constants ($\tau'_{1,2}$). The practical AD-844 device has some finite transadmittance (Y_z) components in the form of shunt-RC arm appearing at its z-node given by $Y_z = sC_z + (1/r_z)$; ; as per databook [12] , the typical values of these parameters are in the range of $3M\Omega \le r_z \le 5M\Omega$ and $3pF \le C_z \le 6pF$. Considering this nonideal effect, we observe that the integrator function F in Equation (1) modifies to:

$$F' = n / [1 + s\{(1+p)/\omega_z\}] \quad (7)$$

Where $n = r_z/R >> 1$, $p = C_z/C << 1$, $\omega_z = 1/C\,r_z$

The integrator quality factor (Q) may be evaluated by writing $F' \equiv \alpha + j\beta$ and then calculating $Q = \beta/\alpha$ which yields $Q = f(1+p)/f_z >> 1$ for the relatively high operating frequency range ($f >> f_z$); for example if $r_z \cong 5\ M\Omega$ and $C_z \cong 6\ pF$ one gets $f_z \cong 5$ kHz. So for frequencies above 5 kHz, the integrator becomes ideal and practically insensitive to the nonideal transadmittance components of the device.

The frequency stability factor ($\boldsymbol{S_f}$) of a sinusoid oscillator is defined as $\boldsymbol{S_f} = (\Delta\theta / \Delta u)\,|_{u=1}$ where $u = f/f_o$ and θ is the loop phase shift. We evaluate the value of $\boldsymbol{S_f}$ after assuming finite transadmittance parameters, given by:

$$\boldsymbol{S_f} = (2\,r_{z\,p})\sqrt{[(1-\varepsilon_T)/R_1R_2]} \quad (8)$$

Where $r_{z\,p}$ is the shunt equivalent $\{1/r_{z\,p} = (1/r_{z1}) + (1/r_{z2})\}$ of the r_z components for the two integrator stages. The stability is quite satisfactory $\boldsymbol{S_f} >> 1$ since $r_{z1,2} >> R_{1,2}$. Here both capacitors are grounded [13] and the parasitic capacitances C_z have an additive effect ($C + C_z$); but since value of C is chosen such that ($C >> C_z$) the resulting deviation would be insignificant, or alternatively, the effect of C_z may be pre-absorbed in value of C.

3. Results

The practical performance of the proposed linear VCO had been examined by both hardware circuit test and with PSPICE simulation. Satisfactory results are obtained in a frequency range of up to 660 kHz with measured THD ≈ 1.11%. It has been verified that operating within the multiplication accuracy of 1%, yields an effective BW ≈ 900 kHz for the ICL-8013 device. So generation above 660 kHz yielded some wave distortion in the proposed realization. Enhancement of f_o –range could thus be obtained using the HA-2556 type multiplier having BW=57 MHz.

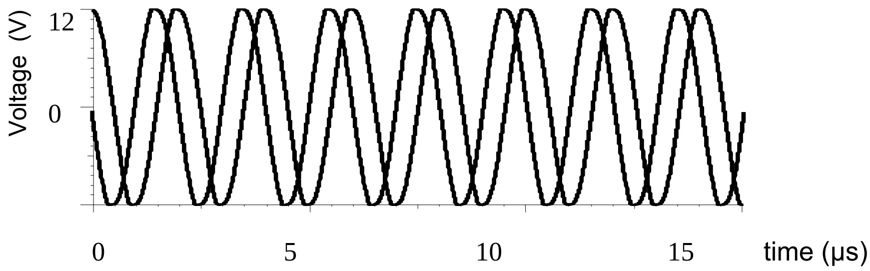
The experimentally generated quadrature waveforms by simulation at 500 kHz along with the spectrum are shown in Figures 3(a) and (b); measured tuning characteristics for two band spreads as set by two RC products are shown in Figure 3(c). Some deviations in f_o on hardware tests relative to those obtained by simulation are observed; these may be due to the presence of some inter-lead capacitances between the breadboard and the IC chip-pins and also due to the parasitic capacitances which were measured to be $C_{z1} \approx 6.6$ pF and $C_{z2} \approx 7.5$ pF while the d.c. supply voltage used is $V_{cc} = 0 \pm 15$V.d.c. for the AD-844 chips. The phase slope of the loop transfer function was observed to be quite high at $f = f_o$ that ensures satisfactory frequency stability. The phase deviation (θ_e) between the quadrature output signals had been measured to be $\theta_e < 3^o$ at 500 kHz - which ensures a better quality of the wave generation compared to other realizations.

It may be mentioned that an MMCC-based linear sinusoid VCO with quadrature signal generation capability had not yet been proposed. A comparison of the performance of the proposed oscillator, with those of some recent designs, based on other types of building blocks [13-18], are summarized in Table 1. It may be observed that the proposed realization utilizes the new building block MMCC and it yields both electronic frequency control with a linear tuning law and quadrature sinusoid generation at low harmonic distortion while frequency stability value is comparatively higher relative to other designs.

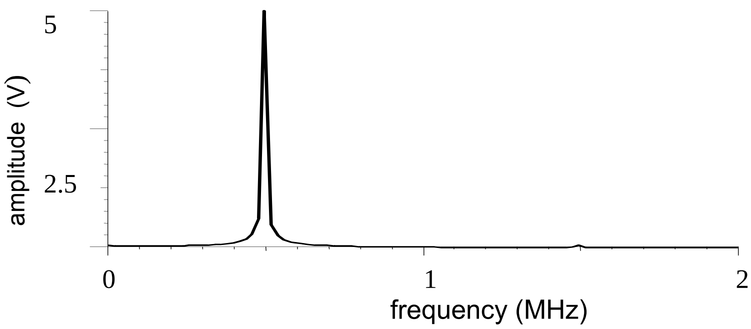
Table 1. Summary on Performance of Some Recent Oscillators

Ref.	Electronic tunability	Quadrature property	f_o (kHz) Tuning range reported	S_f	HD (%)
[13]	No	Yes	20	$\approx 2\, n(1-\varepsilon)=2n$	2.50
[14]	No	No	1	$2/(1+2\varepsilon) \approx 2$	*NI*
[15]	No	Yes	20	$n(2-3\varepsilon) \approx 2n$	1.94
[16]	Yes	No	145	NI	NI
[17]	No	Yes	986	NI	NI
[18]	No	Yes	15.8	NI	2.47
Proposed	Yes	Yes	600	$n\sqrt{(1-\varepsilon_T)} \approx n=r_z/R >> 1$	1.11

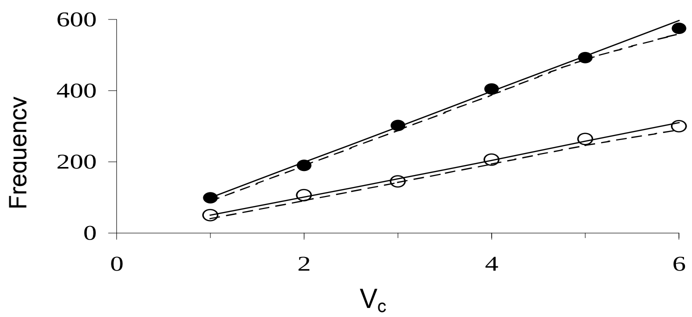
NI: Not indicated



(a) Simulated response at f_o = 500 KHz with k = 0.1/volt and V_c = 5 V.d.c.



(b) Spectrum of the generated signal



(c) Linear tuning characteristics with C=150pF: R = 1KΩ (●) ; R=2KΩ (○) (dotted line by hardware test)

Figure 3. Test results

4. Conclusion

A new MMCC-based linear voltage controlled sinusoid oscillator is presented. The design is essentially a double-integrator loop circuit implemented with readily available IC modules of CFA (AD-844) and four quadrant multiplier (ICL-8013) elements. The practical performance had been verified with both PSPICE simulation and by hardware circuit test in a range of 50 kHz ≤ f_o≤ 600 kHz. The active f_o-sensitivity is low without any significant effect of the parasitic components of the CFA device. The frequency stability is shown to be quite high and the THD of the generated wave had been measured to be low. The phase error between the quadrature output signals had been measured to be $\theta_e < 5^o$ at $f_o \approx 500$ kHz. It may be mentioned here that a linear VCO using the recent MMCC device had not yet been reported in the literature. Such a linear VCO would find various applications in areas of electronic signal processing and communication such as in Phase locked loop (PLL), Frequency synthesis and modulation, as a voltage to frequency transducer etc. The authors are now carrying out further work to extend the functionality of the VCO so as to implement a digitally programmable oscillator wherein a digital signal (e.g. BCD word), after being converted by a Digital to Analog Converter (DAC), would be able to tune and generate a sequence of frequencies leading to FSK or PSK type modulation signal [19].

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