Current-Mode Multiphase Sinusoidal Oscillator Based on Current Differencing Units

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Abstract

This paper describes the design, simulation and experimental verification of a current-mode multiphase sinusoidal oscillator (MSO) consisting of current differencing unit (CDU). The oscillator, composed of *n* 1st-order allpass filters, generates harmonic signals with 2*n* equidistant phase shifts where $n \geq 2$. Compared with conventional MSOs, this circuit is characterized by a minimum number of passive and active components. The experimental verification with the help of commercial integrated circuits is included.

1. Introduction

Wide use of multiphase sinusoidal oscillators (MSO) in telecommunications, power electronics, control technology, measurement systems, analog signal processing, evokes a developing of various circuit topologies of these oscillators, emphasizing the accuracy, stability, low harmonic distortion and low power consumption. In the light of new directions of modern electronics, attention is paid to current-mode applications. Some publications [1,2] use CCII (current conveyor) for implementing the voltage-mode MSOs. However, there is a need of topologies which employ current inputs and outputs. The objective of this direction is higher speed, bandwidth, linearity, low power consumption, and low supply voltage.

The idea of current-mode MSOs is not new. Several constructions using CCII, CDTA were published [3-8] but mostly as theoretical studies without an experimental verification on an oscillator specimen.

The aim of this paper is to give an added value to the area of MSOs in the form of designing novel minimum-components circuit topology, developing filter specimen, and compare its operation with the theoretical assumptions. The analysis of non-ideal case is also added, and the influence of parasitic impedances and other parameters of active elements on the oscillation frequency is evaluated.

2. Principle of operation

There are a few fundamental conceptions of MSO composed of allpass filters. One of the most popular conceptions is based on a single phase oscillator whose output is copied on the other allpass filters providing required phase-shifts of output signals. This solution is preferable for its small dependence of the features of the individual allpass filters between each other. However, widely used conception is based on a few allpass filters in a cascade in a loop. This conception ensures a simple implementation of MSO with equidistant phase shifted outputs, which consists of *n* equivalent allpass filters. The number of phase-shifted output signals is determined by number of allpass filters used. The MSO proposed in this paper utilizes this conception. Figure 1 shows a block diagram of proposed MSO, where an abbreviation APF means All-Pass Filter.

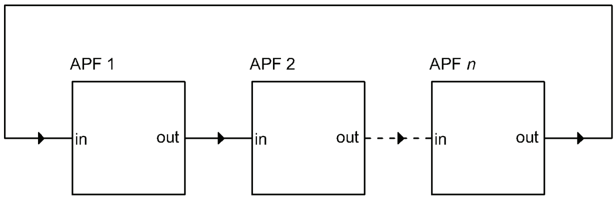


Fig. 1. Block diagram of proposed MSO.

An advantage is stability and direct current-to-current conversions within each block. Our proposal of allpass filter is based on current differencing units.

2.1 CDU (Current Differencing Unit)

CDU [9] is a current-mode active block with two low-impedance inputs (*p* and *n*) and one high-impedance output (*z*). Its operation can be described as follows:

$$I_z = I_p - I_n. \tag{1}$$

The output current I_z is equal to the difference of input currents I_p and I_n. Figures 2 (a) and (b) show its schematic symbol and equivalent circuit. In the ideal case, the impedances of input/output terminals are zero/infinity. Low input impedance reduces the influence of parasitic impedance on the signal transfer.

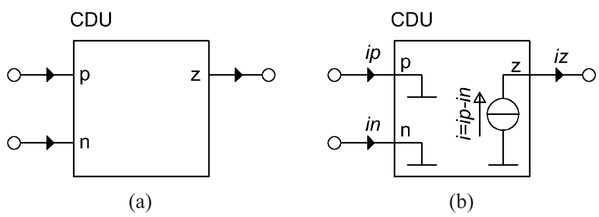


Fig. 2. CDU, (a) schematic symbol, (b) equivalent circuit.

CDU is a sub-block of several active elements [9] for analog signal processing such as CDTA (Current Differencing

Transconductance Amplifier), CDBA (Current Differencing Buffered Amplifier), OTRA (Operating Transresistance Amplifier), DCVC (Differential Current Voltage Conveyor) [9].

2.2 ZC-CDU (Z Copy Current Differencing Unit)

In addition to the CDU, a ZC-CDU is supplemented by two additional terminals, namely *zc* (direct copy of current I_z) and *izc* (copy of inverted current $-I_z$), as illustrated in Figure 6 (b). These terminals are used for generating output currents of the MSO. The primary output current I_z is used for transmitting the signal to other allpass section, thus it cannot be used as the current output. ZC-CDU can be described by the following matrix equation:

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_{zC} \\ I_{izC} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_z \\ V_{zC} \\ V_{izC} \end{bmatrix}. \tag{2}$$

2.3 CDU-based allpass section

The allpass filter in Figure 3 is a basic block of MSO, which is composed of one CDU, one resistor, and one capacitor. This conception was used in the design of quadrature oscillator in [11]. In ideal case, this filter provides frequency independent unity gain, and the phase shift between the output and input current is frequency dependent from within 0 ° to -180 °, being exactly -90 ° at the natural frequency *a* (see Eq. 3).

Routine analysis of the circuit in Figure 3 yields the following transfer function:

$$K_i = \frac{I_o(s)}{I_{in}(s)} = \frac{a-s}{a+s}, \; a = \frac{1}{RC}, \tag{3}$$

where *a* denotes the natural frequency.

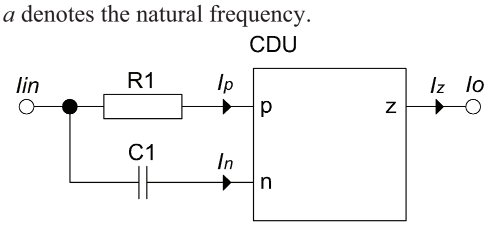


Fig. 3. CDU-based allpass filter [11].

After replacing the CDU by ZC-CDU, two additional current outputs are available which are important for the construction of multiphase oscillator.

2.4 Proposed MSO

The proposed circuit topology of MSO is shown in Fig. 4.

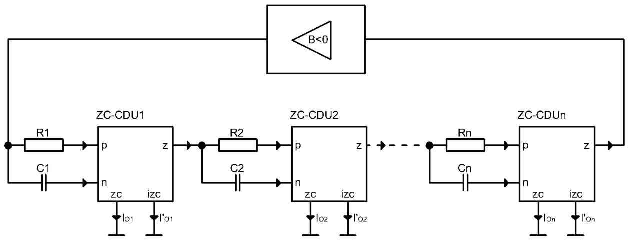


Fig. 4. Current-mode ZC-CDU-based MSO.

It consists of *n* non-inverting allpass sections ($n \geq 2$) in a cascade, followed by inverting controlled current amplifier in the feedback loop ensuring AGC (Automatic Gain Control). Since the total phase shift Φ_Σ in the feedback must be 2π radians at required oscillation frequency, the phase shift $\Delta\Phi$, provided by one allpass section, must fulfill the following condition:

$$\phi_\Sigma = n\Delta\phi + \pi = 2\pi. \tag{4}$$

The above phase shift is then

$$\Delta\phi = \frac{\pi}{n}. \tag{5}$$

For minimum number of allpass sections, i.e. $n = 2$, this phase shift is $\pi/2$ radians.

Taking into account the current gain $B < 0$ of AGC amplifier in Fig. 4, the total loop gain $L(s)$ of the oscillator should be as follows:

$$L(s) = \left(\frac{a-s}{a+s}\right)^n B = -\left(\frac{a-s}{a+s}\right)^n |B| \tag{6}$$

Applying the Barkhausen criterion, we obtain

$$L(j\omega_{osc}) = -\left(\frac{a - j\omega_{osc}}{a + j\omega_{osc}}\right)^n = \frac{1}{|B|}. \tag{7}$$

This complex equation can be rewritten to two well-known real equations

$$|L(j\omega_{osc})| = 1/|B|, \; \angle L(j\omega_{osc}) = 2k\pi, \tag{8}$$

where *k* takes values 0, 1, 2, 3, …. . Combining the above equations (7) and (8), the oscillation frequency (OF) and oscillation condition (OC) can be computed as follows:

OF: $$\omega_{osc} = a \tan\frac{\pi}{2n}, \tag{9}$$

OC: $$|B| = 1. \tag{10}$$

3. Analysis of non-ideal case

A model of one all-pass section no. k is shown in Fig. 5. The model includes major parasitic influences: influence of parasitic impedances, influence of subsequent allpass section, and influence of non-ideal current gains α_p and α_n, being equal to one in the ideal case, and which affect the I_z current according to the formula

$$I_z = \alpha_p I_p - \alpha_n I_n \,. \tag{11}$$

As shown in Figure 5, the following parasitic impedances are considered: R_p and R_n resistances of p and n terminals, and impedance of z terminal, represented by R_z and C_z parameters.

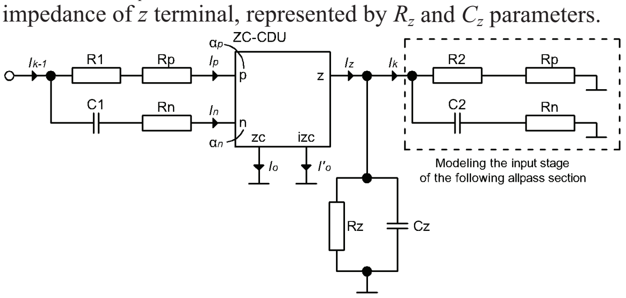


Fig. 5. Model of non-ideal Allpass filter [11].

Under the assumption of identical allpass sections, and after neglecting the influence of internal resistance R_s in the ZC-CDU (see Figure 6 (b)), which does not influence the current transmission within the range of designed oscillation frequencies, the transfer function I_k/I_{k-1} of the model in Figure 6 can be derived in the form

$$H = \frac{I_k}{I_{k-1}} = \frac{I_z}{I_{k-1}}\frac{I_k}{I_z} = H_1 H_2 \,, \tag{12}$$

where

$$H_1 = \frac{I_z}{I_{k-1}} = \alpha_p \frac{1 - sRC\left[\dfrac{\alpha_n}{\alpha_p}\left(1+\dfrac{R_p}{R}\right) - \dfrac{R_n}{R}\right]}{1 + sRC\left(\dfrac{R_n + R_p}{R} + 1\right)} \,, \tag{13}$$

$$H_2 = \frac{I_k}{I_z} = \frac{1}{1 + \dfrac{R + R_p}{R_z}\dfrac{(1+sR_zC_z)(1+sCR_n)}{1+sC(R_n+R_p+R)}} \,. \tag{14}$$

The first part, H_1, models the current transfer from the output of previous (k-1)th section to the output z of the section No. k. This transfer is influenced by real values of resistances R_p and R_n and by current gains α_p and α_n. The second part, H_2, models the current transfer from the output of section No. k to the input terminals of the subsequent section. As shown in Eq. (14), this transfer, being one in the ideal case, can play an important degradation role for low values of parasitic impedance of the z terminal. The following conclusions can be drawn from the analysis of Eqs. (13) and (14):

- The DC gain of one allpass section,

$$H_{DC} = \frac{\alpha_p}{1 + \dfrac{R + R_p}{R_z}} \,, \tag{15}$$

  will be near its ideal value (one) if $\alpha_p \approx 1$ and $R_z >> R + R_p$.

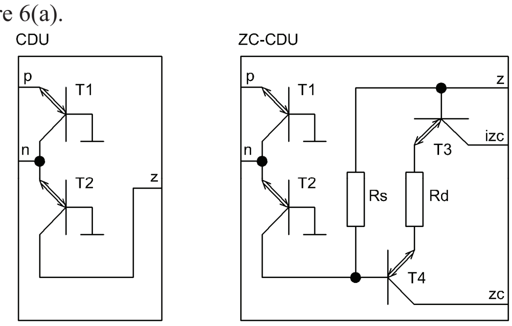
- The proper operation of the allpass section is violated since the zero and pole of H_1 are different in magnitudes. This fact affects both the magnitude response and phase shift of the section, and negatively influences the FO and CO of the oscillator. The only way of eliminating this influence is to keep the conditions $\alpha_p \approx \alpha_p \approx 1$, $R >> R_p$, $R >> R_n$.

- The parasitic resistance R_z should be much higher than the sum of R and R_p. Then H_2 will not negatively influence the section gain.

- A disadvantage of this conception is an attenuation of allpass filters due to subsequently decreasing the amplitudes of output signals from first to last output. This influence can be removed by inserting amplifiers among individual allpass filters or using a controlled gain ZC-CDU as described below.

4. Experimental results

Proposed MSO is primarily intended for integrating on a chip. However, for purpose of experimental verification was MSO specimen implemented using discrete devices. One possible construction of the CDU is based on the so-called diamond transistors (DTs), which are included in the integrated circuit OPA860 [10]. Such CDU implementation is shown in Figure 6(a).



(a) (b)

Fig. 6. Diamond transistor-based (a) CDU, (b) ZC-CDU.

Because the amplitude OC must be fulfilled, a current amplifier was inserted into the feedback loop. This amplifier also ensures AGC function. Its simplified circuit connection is shown in figure 7. The input current I_{in} is inverted to a current I_a (I_a = -I_{in}) which is transferred to a voltage V_a via resistor R_a (V_a = R_aI_a). This voltage is conditioned and led into the LED as well as buffered on the emitter of the second diamond transistor T_b (V_b = V_a). The current I_b, flows through the resistor R_b, is transferred on the output current (I_{out} = I_b = U_b/R_b).

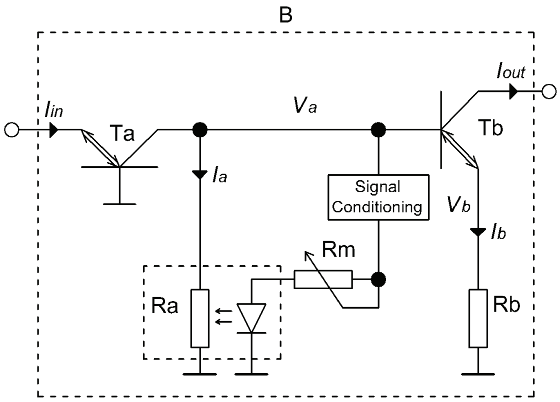


Fig. 7. Controlled current amplifier ensuring AGC.

The transfer function of AGC circuit is given by following equation:

$$K_{IB} = \frac{I_{out}}{I_{in}} = -\frac{R_a}{R_b}. \tag{16}$$

The AGC circuitry employed DTs and, a part of an integrated circuit OPA860, and operational amplifiers. AGC circuit is based on opto-coupler principle: increasing amplitude of V_a lowers value of resistor R_a. Signal generated by the last all-pass in a loop was conditioned by AC coupled non-inverting amplifier followed by precision rectifier and utilized for driving the internal LED of the opto-coupler ensuring gain control.

The amplitude of oscillation in a loop can be controlled by resistor R_m.

The MSO in Figure 4 was designed with three allpass sections, being able to generate up to six-phase signals. The parameters of passive components were designed as follows: $R = 220\ \Omega$, $C = 1$ nF. According to formula (9), the theoretical value of the oscillation frequency is 417.67 kHz. In order to verify the above conception by simulations and by experimental measurement, the MSO was implemented via discrete components. CDU blocks were made of the DTs according to Figure 6.

It follows from the analysis in Section II that the MSO containing three allpass sections provides three sinusoidal waveforms equally phase-shifted by 60 °, and that other three phases can be obtained via inversion of these waveforms.

Figure 8 shows the simulated waveforms of proposed MSO in steady state.

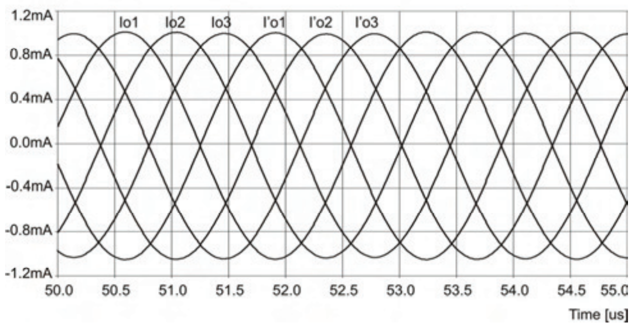


Fig. 8. Simulated waveforms of proposed MSO.

Figure 9 shows three main generated waveforms which were measured on the MSO specimen.

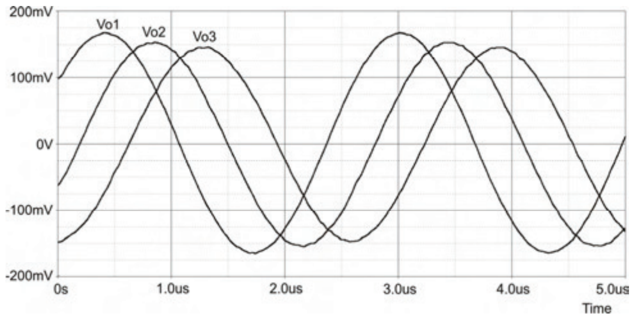


Fig. 9. Measured main waveforms of proposed MSO without output gain settings.

The measurement was done via a sensing of buffered voltages on R_s resistors. A voltage value of 100 mV corresponds to a current of approximately 1 mA. Different signal amplitudes is caused by attenuation of allpass filters. Amplitudes can be adjusted in a simple way by a ratio of two resistors R_s to R_d (see Figure 6 (b)).

Table 1 shows the simulated and measured output spectrum, where the total harmonic distortion (THD) is about 0.06 % and 0.6% respectively. Amplitude of simulated (measured) waveforms is 1 mA (166 mV) and DC component is about -21 nA (1.6 mV). The diference between THD measured and simulated is caused by different electronic devices used for amplitude stabilization.

Table 1. Measured output spectrum of proposed MSO

Harm. NO	Simulated results		Measured results	
	Frequency	Fourier component	Frequency	Fourier component
	MHz	dB	MHz	dB
1	**0.3787**	0	**0.3841**	0
2	0.7574	-69	0.7682	-53
3	1.136	-87	1.152	-46
4	1.515	-70	1.536	-65
5	1.893	-93	1.921	-56
6	2.272	-84	2.305	-57
7	2.651	-84	2.689	-55
8	3.029	-96	3.073	-82
9	3.409	-90	3.457	-63
10	3.787	-86	3.841	-61
THD	**0.06 %**		**0.6 %**	

The measured frequency of oscillation is 384 kHz. It is in a very good agreement with OF obtained by PSpice simulation (378 kHz) and also with OF calculated according to (5 - 14), considering main real influences (395 kHz). Such a good conformity also confirms a correctness of the analysis of non-ideal effects.

6. Conclusions

The paper is aimed at the design, simulation and experimental verification of novel current-mode multiphase sinusoidal oscillator employing current differencing units. Proposed oscillator is composed of n allpass sections. It is able to generate $2n$ equally phase-shifted sinusoidal current signals. The paper includes detailed analysis of real influences as well as experimental results. All experimental results were measured on an oscillator specimen made of three allpass sections and implemented using commercial integrated circuits. Oscillation frequency, computed with regard to major real effects, represents less than 3% deviation from the measured results, and it is also in a very good agreement with PSpice simulation.

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7. References

[1] S. J. G. Gift, "Multiphase Sinusoidal Oscillator Using Inverting-Mode Operational Amplifiers," IEEE Transactions on Instrumentation and Measurement, vol. 47, pp. 986–991, 1998.

[2] M. T. Abuelma'atti and M. A. Al-Qahtani, "A Grounded-Resistor Current Conveyor-Based Active-R Multiphase Sinusoidal Oscillator," Analog Integrated Circuits and Signal Processing, vol. 16, pp. 29–34, 1998.

[3] M. T. Abuelma'atti, "Current-Mode Multiphase Oscillator Using Current Followers," Microelectronics Journal, vol. 25, pp. 457–461, 1994.

[4] C. Loescharataramdee, W. Kiranon, W. Sangpisit and W. Yadum, "Multiphase Sinusoidal Oscillators Using Translinear Current Conveyors and Only Grounded Passive Components," in Proceedings of the Southeastern Symposium on System Theory, pp. 59–63, 2001.

[5] W. Jaikla, M. Sripruchyanun, D. Biolek and V. Biolková, "High Output-impedance Current-mode Multiphase Sinusoidal Oscillator Based on CDTA- allpass filters," International Journal Of Electronics, vol. 7, pp. 811-826, 2010.

[6] W. Tangsrirat, W. Tanjaroen and T. Pukkalanun, "Current-Mode Multiphase Sinusoidal Oscillator Using CDTA-Based Allpass Sections," International Journal of Electronics and Communications (AEÜ), vol. 63, pp. 616–622, 2009.

[7] W. Tangsrirat and W. Tanjaroen, "Current-Mode Multiphase Sinusoidal Oscillator Using Current Differencing Transconductance Amplifiers," Circuits, Systems, and Signal Processing, vol. 27, pp. 81–93, 2008.

[8] D. Biolek, "CDTA—Building Block for Current-Mode Analog Signal Processing," in Proceedings of ECCTD003, Krakow, Poland, vol. III, pp. 397–400, 2003.

[9] D. Biolek, R. Senani, V. Biolková and Z. Kolka, "Active Elements for Analog Signal Processing: Classification, Review, and New Proposals," Radioengineering, vol. 4, pp. 15-32, 2008.

[10] OPA860. Wide Bandwidth Operational Transconductance Amplifier (OTA) and Buffer. Datasheet, Texas Instruments / Burr Brown, SBOS331B, June 2006.

[11] J. Vavra, J. Bajer, D. Biolek, V. Biolkova, "Current-Mode Quadrature Oscillator Employing ZC-CDU-Based All-Pass Filters", in Proceedings of 2011 International Conference on Electronics Engineering and Signal Processing (EESP 2011), pp. 640-644, 2011.