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Electronically Tunable Differential Difference Current Conveyor Using OTAs

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***Abstract*—This paper presents a new electronically tunable differential difference current conveyor (DDCC) using operational transconductance amplifiers (OTAs). Unlike conventional DDCC, the proposed DDCC offers current gain between z– and x–terminal that can be controlled electronically by bias currents. The DDCC–based OTA can be investigated both simulation and experiment tests. The proposed DDCC is used to implement a quadrature oscillator to confirm workability.**

Keywords*—*differential difference current conveyor, operational transconductance amplifier, analog circuit

I. INTRODUCTION

Second-generation current conveyor (CCII) is a popular active building block for application to analog signal processing circuits [1]. Conventional CCII is the device that has three terminals: y–, x–, and z–terminals. The relationship of voltage and current of CCII can be explained as follows: if an input voltage is applied to y–terminal, an equal potential will appear on the x–terminal ($V_x = V_y$) and if an input current is forced into x-terminal, this current will be convoyed to z–terminal ($I_z = I_x$). It should be noted that conventional CCII is a single ended active device, namely single input voltage terminal and single output current terminal. Moreover, the transfer characteristic between z– and x–terminal is unity. To increase the performance of conventional CCII, the CCII that provides current gain between z– and x–terminal have been reported [2]–[5]. The current gain (k) between z– and x–terminal can be given by

$$k = \frac{I_z}{I_x} \tag{1}$$

This current gain offers advantages for analog signal processing applications [6]–[8]. The electronically tunable CCIIs in [2]–[5] implemented using either bipolar or CMOS technology.

OTA is the active device that offers several advantages such as electronic tuning ability, resistorless realization and simple circuitry. The OTA discrete component integrated circuits (ICs) such as LM13600 are commercially available. Thus the performance of OTA–based circuits can be investigated both simulation and experiment. The electronically tunable CCII using OTAs has been reported in [9], [10]. It should be noted that a conventional CCII has a single-input voltage y-terminal which limited for some applications such as negative and positive feedbacks. To achieve addition and subtraction voltage capability of CCII, DDCC has been proposed [10]. This device offers three-input y-terminals and the electrical symbol can be shown as Fig. 1. The voltage and current relationship can be expressed as

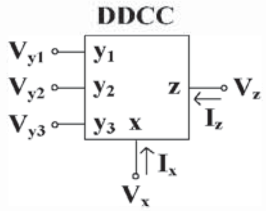

Fig. 1. Electrical symbol of conventional DDCC.

$$\begin{pmatrix} I_{y1} \\ I_{y2} \\ I_{y3} \\ V_x \\ I_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \beta_1 & -\beta_2 & \beta_3 & 0 & 0 \\ 0 & 0 & 0 & \alpha & 0 \end{pmatrix} \begin{pmatrix} V_{y1} \\ V_{y2} \\ V_{y3} \\ I_x \\ V_z \end{pmatrix} \tag{2}$$

where β_1 is the voltage gain between x- and y_1-terminal, β_2 is the voltage gain between x- and y_2-terminal, β_3 is the voltage gain between x- and y_3-terminal and α is the current gain between z- and x-terminal (ideally: $\beta_1 = \beta_2 = \beta_3 = \alpha = 1$). It should be noted that property of DDCC is similar the conventional CCII, except addition and subtraction voltage capability can be obtained at y_1, y_2 and y_3-terminals. However, conventional DDCC is still not provided the current gain between z- and x-terminals.

This paper a new electronically tunable DDCC has been proposed. It is realized using OTAs discrete component ICs. The current gain between z- and x-terminals can be controlled electronically. The proposed electronically tunable DDCC has been implemented using LM13600 discrete component integrated circuits (ICs). The proposed DDCC is used to realize a quadrature oscillator to confirm workability.

II. PROPOSED CIRCUIT

Fig. 2 shows the electrical symbol of electronically tunable DDCC (EDDCC) and its characteristics can be given by

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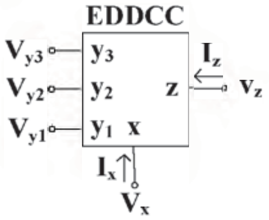

Fig. 2. Electrical symbol of EDDCC.

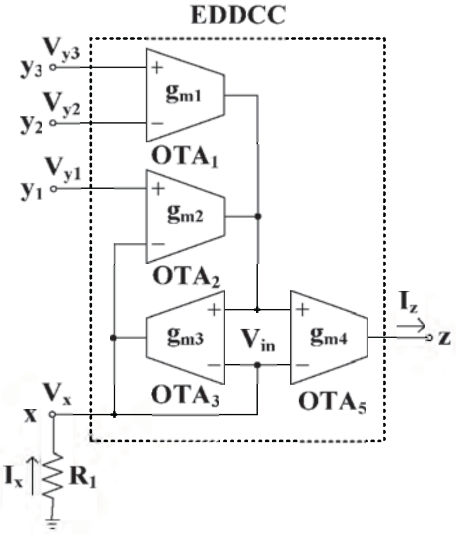

Fig. 3. Proposed EDDCC using OTAs.

$$\begin{pmatrix} I_{y1} \\ I_{y2} \\ I_{y3} \\ V_x \\ I_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \beta_1 & -\beta_2 & \beta_3 & 0 & 0 \\ 0 & 0 & 0 & k & 0 \end{pmatrix} \begin{pmatrix} V_{y1} \\ V_{y2} \\ V_{y3} \\ I_x \\ V_z \end{pmatrix} \tag{2}$$

where k is the current gain of EDDCC.

The proposed EDDCC is shown in Fig. 3. It consists of four OTAs. Assume that OTA$_1$ to OTA$_3$ are identical, the voltage relationship between V_x and V_{y1}, V_{y2}, V_{y3} can be expressed by

$$V_x = \frac{(g_{m2}g_{m3}R_{in}R_1)V_{y1} - (g_{m1}g_{m3}R_{in}R_1)V_{y2} + (g_{m1}g_{m3}R_{in}R_1)V_{y3}}{1 + g_{m3}R_1 + g_{m2}g_{m3}R_{in}R_1} \tag{3}$$

where g_{mi} is the transconductance of OTA$_i$, R_1 is the given resistor and R_{in} is the input resistance of OTA$_3$: for LM13600 OTA, resistance R_{in} is approximately 130 kΩ. The voltage transfer ratios β_i are:

$$\beta_1 = \frac{g_{m2}g_{m3}R_{in}R_1}{1 + g_{m3}R_1 + g_{m2}g_{m3}R_{in}R_1} \tag{4}$$

$$\beta_2 = \frac{g_{m1}g_{m3}R_{in}R_1}{1 + g_{m3}R_1 + g_{m2}g_{m3}R_{in}R_1} \tag{5}$$

$$\beta_3 = \frac{g_{m1}g_{m3}R_{in}R_1}{1 + g_{m3}R_1 + g_{m2}g_{m3}R_{in}R_1} \tag{6}$$

From (4)-(5), assume that $g_{m2}g_{m3}R_{in}R_x \gg 1 + g_{m3}R_1$, the relationship of $V_x \approx V_{y1} - V_{y2} + V_{y3}$ can be achieved when $g_{m1} \approx g_{m2} \approx g_{m3}$ are given. From Fig. 2, the output current of OTA$_3$ equaled to current I_x which can be given by

$$I_x = g_{m3}(V_{in} - V_x) \tag{7}$$

The input terminal of OTA$_4$ is parallel connection of OTA$_3$: hence the output current of OTA$_4$ can be given by

$$I_z = g_{m4}(V_{in} - V_x) \tag{8}$$

From (4), it can be rewritten as $V_{in} - V_x = I_x/g_{m3}$ and replacing it into (3), the relationship between currents I_z and I_x can be given by

$$I_z = \frac{g_{m4}}{g_{m3}} I_x \tag{9}$$

The current gain k is:

$$k = \frac{g_{m4}}{g_{m3}} \tag{10}$$

Thus the current gain k can be controlled by adjusting g_{m4} while g_{m3} is fixed to constant and it should be given as $g_{m1} = g_{m2} = g_{m3}$ for achieving addition and subtraction voltage property $V_x = V_{y1} - V_{y2} + V_{y3}$ of DDCC.

From Fig. 3, it can see that z-terminal is provided a positive current output (EDDCC+). If a negative current output z-terminal (EDDCC-) is required, it can be obtained by adding additional OTA and its input terminals connect interchange with input terminals of OTA$_4$.

The resistance at x-terminal is:

$$R_x \approx \frac{1}{g_{m3}} \tag{11}$$

Finally, the resistances at y– and z–terminals of EDDCC equal to the input and output resistances of LM13600 OTA which possess high–impedance level.

III. SIMULATION AND EXPERIMENTAL RESULTS

The proposed EDDCC has been implemented using LM13600 OTA discrete component ICs. The power supplies were given as ±5 V. The bias currents of OTA$_1$ to OTA$_3$ were fixed by using the resistance of 150 kΩ (I_{ABC} = 24.8 µA: g_m = 0.48 mS) while the bias current of OTA$_4$ was used to adjust current gain. Both simulation and experiment tests have been investigated. Fig. 4 shows the simulated DC curves V_x versus V_{y1} and the voltage error (V_{y2} and V_{y3} were grounded). From this figure, when V_{y1} was varied in range of -120 to 120 mV, the simulated voltage offset at V_{y1} = 0 was 0.76 mV and the voltage error was less than 0.14 mV when V_{y1} = ± 50 mV and less than 5.5 mV when V_{y1} = ± 100 mV. The simulated DC curves I_z versus I_x and the current error was shown in Fig 6. Simulated result shows that when I_x was varied in range of -25 to 25 µA, the simulated current offset at I_x = 0 was 0.4 µA, the current error was less than 0.5 µA when I_x = ± 15 µA and less than 0.65 µA when I_x = ± 25 µA.

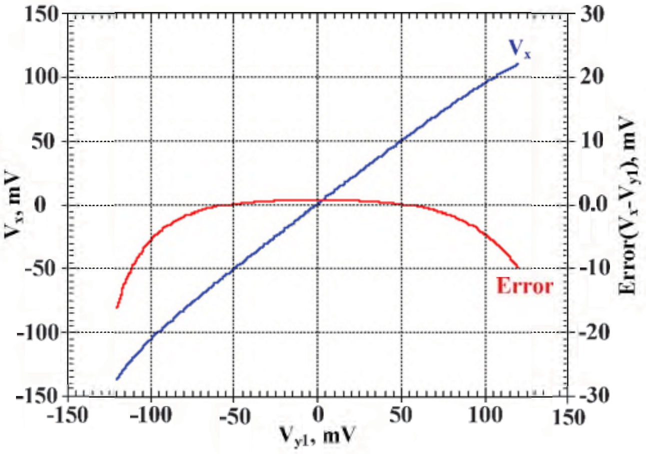

Fig. 4. DC characteristic between V_x and V_{y1} and its voltage error.

TABLE I. SUMMARIZED PERFORMANCES OF EDDCC.

Parameters	Value
Supply voltage	±5 V
OTA	LM13600
Bias current (I_{ABC}) (I_{ABC} = 150 kΩ)	24.8 µA
V_x/V_{y1} and V_x/V_{y2} (no load)	-100 mV to 100 V
V_x/V_{y3} (no load)	-500 mV to 500 mV
DC current range	-25 µA to 25 µA
-3dB bandwidth (V_x/V_{yi})	4.5 MHz
-3dB bandwidth (I_z/I_x)	6.6 MHz
R_{yi}: C_{yi}	411 kΩ: 3.07 pF
R_x: L_x	20.5 Ω: 9.68 µH
R_{zi}: C_{zi}	73 MΩ: 0.76 pF

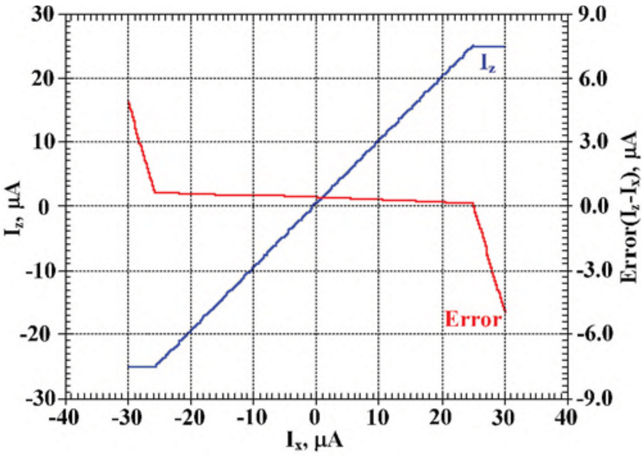

Fig. 5. DC characteristic between I_z and I_x and the current error.

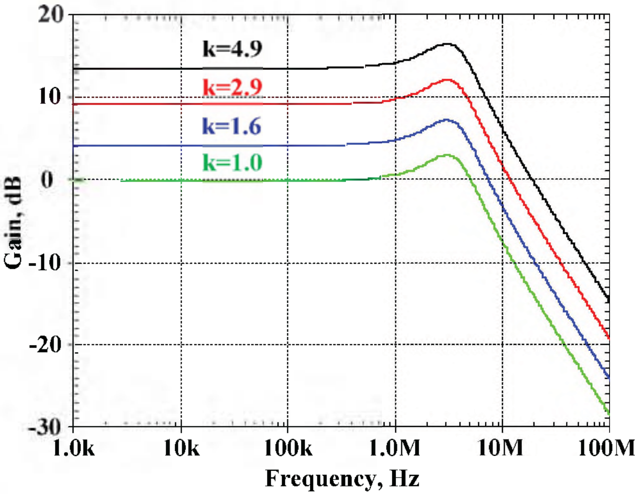

Fig. 6. Frequency responses of different current gains.

The frequency response of different current gains I_z/I_x was simulated and shown in Fig. 6. In this case, g_{m3} was fixed as 0.48 mS (I_{ABC} = 24.8 µA: R_{ABC} = 150 kΩ) and g_{m4} was varied as 0.79 mS (I_{ABC} = 40.67 µA: R_{ABC} = 91 kΩ), 1.39 mS (I_{ABC} = 71.98 µA: R_{ABC} = 51 kΩ), 2.35 mS (I_{ABC} = 121.5 µA: R_{ABC} = 30 kΩ). Summarized performance of proposed EDDCC was shown in Table I.

IV. APPLICATION EXAMPLE

The proposed quadrature oscillator is shown in Fig. 7. It is composed of two EDDCCs, two grounded capacitors and three grounded resistors. The characteristic equation of Fig. 7 can be expressed as

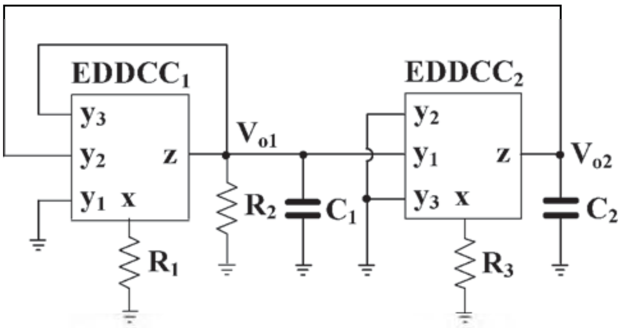

Fig. 7. Proposed voltage-mode quadrature oscillator.

$$s^2C_1C_2R_1R_2R_3 + sC_2R_3(R_1 - k_1R_2) + k_1k_2R_2 = 0 \quad (12)$$

The condition of oscillation (CO) and the frequency (FO) of oscillation can be obtained as

$$R_1 = R_2 \quad (13)$$

$$\omega_o = \sqrt{\frac{k_1k_2}{C_1C_2R_1R_3}} \quad (14)$$

It can see from (13) and (14) that the condition of oscillation can be controlled by adjusting R_2 and the frequency of oscillation can be controlled by k_2 or R_3 without disturbing the condition of oscillation. It should be noted that electronic control of circuit can be obtained.

From Fig. 3, EDDCC$_2$ along with C_2 and R_3 form of the lossless integrator. Hence, the phase difference ϕ between V_{o1} and V_{o2} is given by

$$\varphi = \pi - \tan^{-1}(\omega C_2R_3) \quad (15)$$

At ω=ω$_o$, (15) can be obtained as ϕ=π/2, ensuring that the currents V_{o1} and V_{o2} are in quadrature.

The quadrature oscillator in Fig. 7 was designed with C_1 = C_2 = 0.01 µF, R_1 = R_3 = 1 kΩ, k_2 = 1 and using proposed EDDCC in Fig. 3. The resistance R_2 (variable resistor) is used to control the condition of oscillator. Fig. 8 shows measured output waveforms for k_2 = 1. The frequency of oscillation of 15.2 kHz was obtained while theoretical value should be 15.9 kHz. Fig. 9 shows the quadrature output waveform in Fig. 10 that was verified through the XY mode. Thus, it can be confirmed that the quadrature oscillator provides output voltages V_{o1} and V_{o2} with 90° phase different.

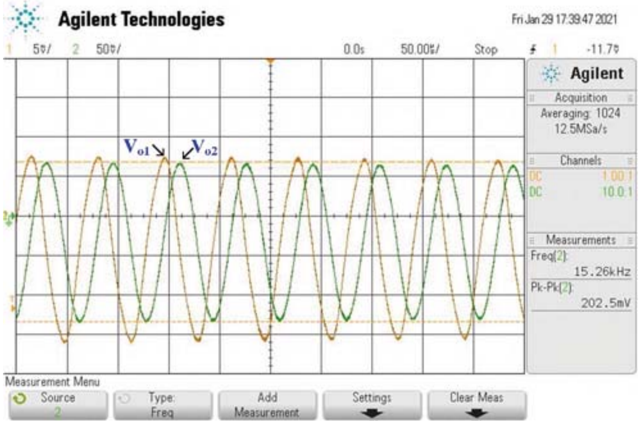

Fig. 8. The experimental output waveforms V_{o1} and V_{o2}.

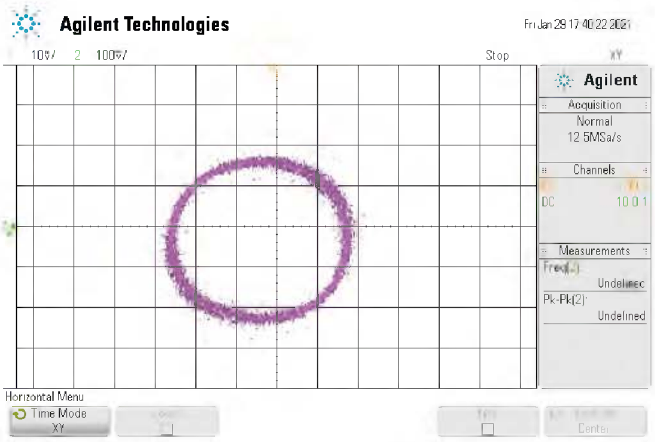

Fig. 9. The experimental result for XY plot of outputs in Fig. 8.

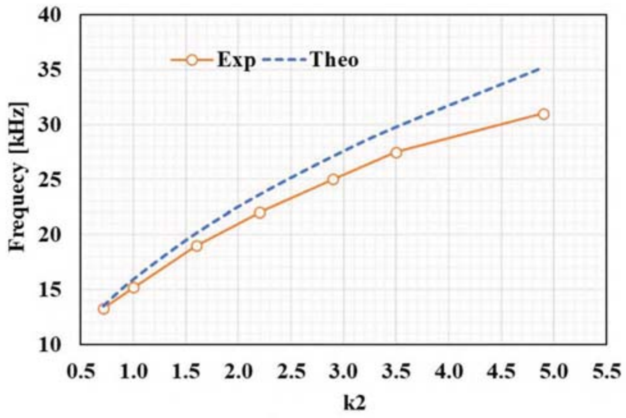

Fig. 10. FO against current gain k_2.

The experimental result of the FO by changing the value of the current gain k_2 was shown in Fig. 10. It can be used to confirm that EDDCC–based circuit provides an electronic tuning capability. However,

V. CONCLUSIONS

In this paper, a new electronically tunable DDCC based on OTA is proposed. Unlike, conventional DDCC, the proposed electronically tunable DDCC provides electronic tuning capability. It can be shown that electronically tunable DDCC–based circuits, both simulation and experimental tests can be investigated. The proposed circuit has been used to realize a quadrature oscillator to confirm electronic tuning capability and workability of new circuit.

REFERENCES

[1] R. Senani, D. R. Bhaskar, A. K. Singh, Current conveyors variants, applications and hardware implementations, Springer International Publishing Switzerland, 2015.

[2] W. Surakampontorn, K. Kumwachara, “CMOS-based electronically tunable current conveyor,” Electronics Letters, vol. 28, pp. 1316-1317, 1992.

[3] A. Fabre, N. Mimeche, “Class A/AB second generation current conveyor with controlled current gain”, Electronics Letters, vol. 43, pp. 82-91, 1996.

[4] S. Minaei, O. K. Sayin, H. Kuntman, “A new CMOS electronically tunable current conveyor and its application to current-mode filters,” IEEE Transactions on Circuits and Systems–I: Regular Papers, vol. 53, pp. 1448-1458, 2006.

[5] M. Kumngern, “A new CMOS second generation current conveyor with variable current gain,” in Proceedings of 2012 IEEE International Conference on Circuits & Systems (ICCAS), Malaysia, 2012, pp. 1-4.

[6] P. Pawarangkoon, W. Kiranon, “Electronically tunable floating resistor,” International Journal of Electronics, vol. 91, pp. 665–673, 2004.

[7] M. Kumngern, W. Jongchanavawat, K. Dejhan, “New electronically tunable current-mode universal biquad filter using translinear current conveyors,” International Journal of Electronics, vol. 97, pp. 511–523, 2010.

[8] M. Kumngern, J. Chanwutitum, K. Dejhan, “Electronically tunable multiphase sinusoidal oscillator using translinear current conveyors,” Analog Integrated Circuits and Signal Processing, vol. 65, pp. 327–334, 2010.

[9] S. Pookaiyaudom, K. Samootrut, “Efficient circuit implementations of current conveyors, negative impedance converters and nonlinear impedance converters using operational transconductance amplifiers,” International Journal of Electronics, vol. 64, pp. 941–945, 1988.

[10] V. Riewruja, W. Petchmaneelumka, “Floating current-controlled resistance converters using OTAs,” AEU-International Journal of Electronics and Communications, vol. 62, pp. 725-731, 2008.

[11] W. Chiu, S.–I. Liu, H.–W. Tsao, J.–J. Chen, “CMOS differential difference current conveyors and their appli-cations,” IEE Proceeding of Circuits, Devices, System, vol. 143, pp. 91–96, 1996.