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<td>Winai Jaikla¹, Montree Siripruchyanun²</td>
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<td>Winai Jaikla¹, Montree Siripruchyanun²</td>
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A Systematic Design of Electronically Tunable Ladder Filters Employing DO-OTAs

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Abstract—A systematic design of continuous-time current-mode ladder filter using Dual-Output OTAs (DO-OTAs) is presented. The proposed technique is based on leapfrog simulation of RLC ladder filter using only DO-OTAs and grounded capacitors that lead to simple structure, easy to design and suitable for IC fabrication. A fifth-order Chebyshev low-pass filter and a sixth-order Chebyshev band-pass filter which retain a minimum requirement of passive elements and have an advantage of electronically tunable will be introduced. The feasibility of realization strategy is confirmed through PSPICE circuit simulations.

I. INTRODUCTION

Double terminated passive RLC ladder filters are well known on having an inherent advantage over active filter in terms of their sensitivity to component tolerances. There are several methods to extract this benefit from the prototype passive filter using the opamp-based RC-active and OTA-C-based circuits [1]. The leapfrog structure seems to receive more popular sine it shares the entire low sensitivity characteristic and low component spread of the precedent RLC filter. Traditionally, the simulation is based on modeling all circuit equations as voltage signals [1]. Recently, current-mode signal processing has been received substantial consideration owing to its higher performance properties. Consequently, many suggestions of current-mode leapfrog ladder filter had been published employing OTAs [2] and CCIIs [3] as the active building blocks. However, all of them are established from simulating the operation of the ladder by mean of realizing the transfer function, which require a lot of active and passive elements and sometime the sensitivity may not necessitate being low. The implementation of leapfrog filter using current differential buffered amplifiers or CDBAs has been proposed [4], which can perform high frequency and low voltage supply operation. This scheme can simplify the signal flow graph of leapfrog filter and then realize each circuit element one by one, hence the low sensitivity basis is promised. Unfortunately, several floating resistors are required for voltage to current conversion and the utilized frequency is exactly fixed by determined passive elements.

This paper follows the idea of realizing the voltage-current relationships of each element corresponding to the prototype RLC, filters one by one. OTA is chosen to function as a V-to-I converter cell regenerating all voltage parameter into current form because it is a commercially available component. This proposed scheme possesses many advantages. Firstly, the structure is very simple and easy to design. No any external resistor is required, which can save the area in case of fabricating in a silicon chip. Moreover, the center frequency can be tuned electronically by adjusting the bias current of OTAs. This will be useful in redeeming when the values of passive devices are deviated; including changing the system’s characteristic is also very comfortable.

This work is organized as follows. Firstly, the Dual-output Operational Transconductance Amplifier will be introduced. The simulated elements, which are grounded resistance simulator, grounded/floating inductance simulators and floating capacitance simulator, are included in Section II. The filter design methodology will be given in Section III. Section IV shows the simulation results. They compare the results of filter synthesis from simulated and ideal elements.

II. PRINCIPLE OF OPERATION

A. The Dual-Output Operational Transconductance Amplifier (DO-OTA)

Since the proposed circuits are based on DO-OTAs, a brief review of the DO-OTA is given in this section. An ideal DO-OTA has infinite input and output impedances. Output current of the DO-OTA is given by

\[ I_{O+} = I_{O-} = g_m(V_1 - V_2). \]  

(1)

Where \( g_m \) is the transconductance parameter of an OTA. For a bipolar OTA, the transconductance gain can be expressed by

\[ g_m = \frac{I_B}{2V_T}. \]  

(2)

Where \( I_B \) and \( V_T \) are bias current and thermal voltage, respectively. The symbol of the DO-OTA is shown in Fig. 1.
B. Grounded Resistance Simulator

The OTA-based grounded resistance simulator is shown in Fig. 2 [5]. From routine analyzing the circuit in Fig. 2, we will get the equivalent grounded resistance as

\[ R_{eq} = \frac{1}{g_m} = \frac{2V_T}{I_B}. \] (3)

From Eq. (3), the resistance value is controlled by adjusting \( I_B \).

![Figure 2. Grounded resistance simulator](image1)

C. Grounded Inductance Simulator

Fig. 3 depicts the proposed grounded inductance simulator [6]. Considering the circuit in Fig. 3 and using OTA properties in Section A, we will receive

\[ Z_L = \frac{V_o}{I_L} = \frac{sC}{g_{m2}g_{m1}}. \] (4)

From Eq. (4), it is obvious that the circuit shown in Fig. 2 simulates a grounded inductance with a value

\[ L_{eq} = \frac{C}{g_{m2}g_{m1}} = 4V_T^2C. \] (5)

It can be clearly seen from Eq. (5) that the inductance value \( L_{eq} \) can be adjusted electronically by either \( I_{B1} \) or \( I_{B2} \).

![Figure 3. Grounded inductance simulator](image2)

D. Floating Inductance Simulator

Fig. 4 depicts the proposed floating inductance simulator, where \( I_{B1} \) and \( I_{B2} \) are input bias currents of the OTA1 and OTA2, respectively. Considering the circuit in Fig. 4 and using the OTA properties in section A, we will receive

\[ Z_L = \frac{V_1 - V_2}{I_L} = -\frac{sC}{g_{m2}g_{m1}}. \] (6)

From Eq. (6), it is obvious that the circuit shown in Fig. 4 simulates a floating inductance with a value

\[ L_{eq} = \frac{C}{g_{m2}g_{m1}} = 4V_T^2C. \] (7)

It can be clearly seen from Eq. (7) that the inductance value \( L_{eq} \) can be adjusted electronically by either \( I_{B1} \) or \( I_{B2} \).

![Figure 4. Floating inductance simulator](image3)

E. Floating Capacitance Simulator

Fig. 5 depicts the floating capacitance multiplier originated from a grounded capacitor [7]. Considering the circuit in Fig. 5 and using OTA properties in Section A, we will receive the input impedance as

\[ Z_C = \frac{V_1 - V_2}{V_1} = \frac{g_{m3}R_{m1}}{sCg_{m1}g_{m2}}. \] (8)

From Eq. (8), it is clearly seen that the circuit can provide the floating capacitor with a value

\[ C_{eq} = \frac{I_{B1}I_{B2}}{I_{B3}I_{B4}}C. \] (9)

![Figure 5. Floating capacitance simulator](image4)
currents. Then the capacitive value, with adjusting by input bias currents, is very widely tuned. For example, the minimum input bias current can be as low as nano-ampere range while the maximum input bias current can be as high as milli-ampere range.

III. FILTER DESIGN METHODOLOGY

A current-mode fifth-order low-pass RLC ladder filter shown in Fig. 6 is adopted as an example. It comprises the minimum requirement of DO-OTAs and capacitors. There is no obligation of any external resistor, even the terminated resistor, Rs and Ro; are also implemented using DO-OTA (in Section B). Not only the attempt to eliminate the passive components, it is the necessary for tuning pole frequency feature. Furthermore, this composition has several high impedance outputs, which allow to be easily cascaded without any additional matching circuits.

![Figure 6. Current-mode fifth-order Chebyshev low-pass RLC ladder filter](Image)

In addition, deriving the RLC ladder band-pass filter with this procedure is also possible. Consider a current-mode sixth-order band-pass filter in Fig. 7. In this case, the floating and grounded R, L and C branches can be realized using the basic block as shown in Section II.

IV. SIMULATION RESULTS

To prove the performances of the proposed principle, the PSPICE simulation program was used for the examination. The PNP and NPN transistors employed in the proposed circuit were simulated by respectively using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T [8] with ±2.5V supply voltages and all bias currents I_B were set to be 100μA, except that the I_B of grounded resistances Rs and Ro were set to be 200μA to obtain resistance value of 276Ω. Fig. 8 depicts schematic description of the DO-OTA used in the simulations.

![Figure 7. Current-mode sixth-order RLC band-pass filter](Image)

Furthermore, C1=C2=10μF, C_{eq1}=C_{eq2}=1nF and C_{eq3}=10μF are taken to obtain inductance and capacitance of 328μH and 10μF, respectively. Comparison of the ideal and simulated current-mode sixth-order RLC band-pass filter responses is depicted in Fig. 11. In addition, center frequencies can be adjusted by varying the input bias current of the DO-OTAs, as shown the results in Fig 12.

![Figure 8. Internal construction of the DO-OTA](Image)

To show the frequency domain performance of the current-mode fifth-order Chebyshev low-pass RLC ladder filter in Fig. 6, it was simulated with PSPICE program. C1=C2=C3=10μF and C_{eq1}=C_{eq2}=1nF are chosen to obtain inductance value of 328μH. The simulated frequency responses of the ideal and simulated low-pass ladder filter are compared in Fig. 9. The result is very close to ideal filter implemented from the practical passive elements. Tuning ability is also simulated and shown in Fig. 10 by varying bias current to 50μA 100μA and 150μA. It is found that the pole frequency can be tuned by the input bias current.

![Figure 9. Compared results of current-mode fifth-order Chebyshev low-pass RLC ladder filter](Image)

![Figure 10. Results for cut-off frequency tunability of the simulated low-pass RLC ladder filter](Image)
CONCLUSIONS

A design of RLC ladder filters using simulated elements (resistors, inductors and capacitors) based on the Dual-Output Operational Transconductance Amplifiers (DO-OTAs) has been described. The design strategy is very simple and requires the minimum passive components. The pole or center frequency can be tuned electronically by controlling the bias currents of DO-OTAs, which is very helpful in compensating unmatched components as well as varying the characteristic without changing any device. Fifth-order Chebyshev low-pass filter and sixth-order Chebyshev band-pass filter are derived as examples. Actually, the simulated elements can be applied in any filter functions. The PSPICE simulation results give a good agreement with the theoretical expectations.

REFERENCES