Current Follower Macromodel For Active Circuit Simulation

Erhan Ergün[1] and Mustafa Ulutaş[1]

[1]Ondokuz Mayıs University, Samsun, Turkey
erergun@omu.edu.tr, ulutas@omu.edu.tr

Abstract

At this work, a novel macromodel circuit is proposed for current followers. Proposed macromodel can handle both linear and non-linear behavior of current followers and saves simulation time and design effort for engineers explicitly. Proposed circuit is tested on a current follower circuit with AC and DC inputs. Finally biquad filter which uses current followers as active elements is simulated in time domain with macromodel and element model appropriately

1. Introduction

Macromodel is the circuit which enables to simulate complex and multi-element circuits with reduced number of active and passive basic circuit elements. Simulation programs, imports the physical elements such as resistors, diodes and transistors, into a mathematical model and makes the simulation. Errors of simulation are based on the representation capabilities of model of the physical circuit. In general, method for improving the accuracy is to add more elements to model of the circuit and consequently it costs more simulation effort.

Simulation with the advanced model of transistors means to work with sub-circuits built with at least ten elements for each transistors and simulation of an integrated circuit which consists of thousands of transistor and analog/digital element means a great computational effort. It costs lots of time and requires more computing effort respectively. Time-saving properties of macromodels make them preferable for simulation. On the other hand, macromodels are very suitable elements for non-linearity analysis.

Several macromodel proposals are given for operational amplifiers, current conveyors, four terminal floating nullors and operational transconductance amplifiers have been given in literature [1-6]. Although some of them have focused on linear behavior, general trend is to handle both linear and non-linear characteristics of related circuits. At this work, a macromodel circuit is proposed for current followers, which consists of 6 resistors, 3 capacitors, 2 inductances, 4 diodes, 5 independent, 2 dependent voltage sources and 2 dependent current sources.

2. Macromodel Circuit

Representation of current follower is given in Fig. 1. In ideal case, X is the input terminal with $R_X = 0$, Z+ and Z- are the output terminals with $R_Z = \infty$ and current gain is +1 for Z+ and -1 for Z-. In practice, there are several non-idealities to be handled in macromodels.

Proposed macromodel is given in Fig. 2. Only Z+ output is shown but Z- terminal can be obtained by adding a circuit which has the same topology and elements with output stage consists of V_{DD}, V_{SS}, V_{D3}, V_{D4}, R_{D3}, R_{D4}, D3, D4, C_{O1}, R_{O1} and k_2x_2. Formulas of circuit elements are given in Table 1.

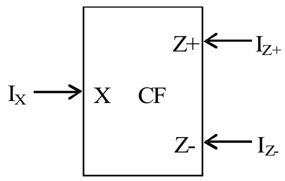

Fig. 1. Representation of current follower

Table 1. Formulas of elements in macromodel

Element	Equation	Element	Equation
R_{CX1}	r_{Xmin}	L_{X2}	$\dfrac{Q}{\omega_c}$
C_{X1}	$\dfrac{1}{BW_X R_{CX1}}$		$Q=\sqrt{\dfrac{4A_m^2+4A_m\sqrt{A_m^2-1}}{8}}$
R_{X1}	r_{Xmax}	C_{X2}	$\dfrac{1}{\omega_c^2 L}$
L_{X1}	$\dfrac{1}{\omega_{cX}^2 C_{X1}}$		$\omega_c=\dfrac{\omega_m}{\sqrt{1-\dfrac{1}{2Q^2}}}$
V_{OX}	V_{Xoff}	R_{X2}	1
V_{D1}	$I_{Xmax}.h_1$	V_{D3}	V_{DD} - V_{Omax}
V_{D2}	$I_{Xmin}.h_2$	V_{D4}	V_{Omin} - V_{SS}
h_1	$\dfrac{\Delta V_X}{\Delta I_X}$ ($I_X > I_{Xmax}$)	R_{D3}	$\dfrac{\Delta V_O}{\Delta I_Z}$ ($V_O > V_{Omax}$)
h_2	$\dfrac{\Delta V_X}{\Delta I_X}$ ($I_X < I_{Xmin}$)	R_{D4}	$\dfrac{\Delta V_O}{\Delta I_Z}$ ($V_O < V_{Omin}$)
k_1	1	C_{O1}	Output capacitance
k_2	1+ε	R_{O1}	Output resistance

R_{CX1}, C_{X1}, L_{X1} and R_{X1} elements give a band-pass filter function and they are used to simulate input impedance relation versus frequency. If we assume that R_{X1} is too small, ω_C is the center frequency of this filter and BW_X is the bandwidth where the impedance goes to -3dB of its peak value. BW_X and ω_C values can be obtained by applying an AC test current into the X terminal of the original current follower circuit.

V_{OX} source represents the DC offset voltage. Combination of h_1i_X, h_2i_X V_{D1}, V_{D2}, D1, D2 elements determines the upper and lower limits of input voltage-current relation curve in linear region. I_{Xmax} and I_{Xmin} values are the upper and lower linear region limits of input current of original follower. They can be obtained by applying a DC test current into the X terminal of the original current follower circuit.

C_{X2}, L_{X2}, and R_{X2} elements give a second order low-pass filter function and they have been placed to the circuit for modeling the relation between current gain and frequency. R_{X2} is taken into account as 1. Quality factor Q and center frequency ω_c of second-order filter is needed to compute the element of this stage. These values can be obtained from the AC current gain of original current follower circuit. A_m is the peak value of current gain and ω_m is the frequency of this peak gain. Q, ω_c, C_{X2} and L_{X2} values can be computed as shown in Table 1. Furthermore, AC current gain can be in first-order low-pass form. In this case, L_{X2} is taken to be zero and C_{X2} becomes $1/(2\pi f_{-3dB})$.

R_{O1} and C_{O1} are output resistances and capacitances of macromodel circuit. V_{D3}, V_{D4}, R_{D3}, R_{D4}, D3 and D4 elements determine upper and lower limit of output voltage. R_{D3} and R_{D4} resistors determine the slope of I-V curve in non-linear range [2]. V_{Omax} and V_{Omin} are the maximum and minimum values of linear voltage range at output terminal. ε is current tracking error in the original current follower circuit.

3. Application of Macromodel

Macromodel approach is tested on a current follower circuit given in Fig. 3. Computed values of macromodel elements are given in Table 2. Elements of Z- terminal of macromodel are named with V_{D5}, V_{D6}, R_{D5}, R_{D6}, D5, D6, C_{O2}, R_{O2} and k_2x_2.

Three test input is applied on macromodel circuit. Input impedance and current gain versus frequency is given in Fig. 4 and Fig. 5. Voltage-current characteristic of input terminal is given in Fig. 6.

Table 2. Elements values of macromodel applied for current follower circuit in Fig. 3

Element	Value	Element	Value
L_{X1}	4.69μH	D_1- D_6	Ideal
C_{X1}	0.03pF	V_{D1}	44.5V
R_{CX1}	39.7kΩ	h_1	$0.5\ 10^6$
R_{X1}	64.18Ω	V_{D2}	231
V_{OX}	0.59mV	h_2	$5\ 10^6$
k_1	1	V_{D3}	0.2V
L_{X2}	0.84nH	V_{D4}	0.1V
C_{X2}	0.168nF	R_{D3}	3.2kΩ
R_{X2}	1	R_{D4}	680Ω
k_2	1	V_{D5}	0.15V
R_{O1}	1.52MΩ	V_{D6}	0.15V
C_{O1}	0.28pF	R_{D5}	700Ω
k_3	-1	R_{D6}	2.5kΩ
R_{O2}	1.79MΩ	V_{DD}	1.5V
C_{O2}	3nF	V_{SS}	-1.5V

4. Performance Test on a Butterworth Filter

A current-mode single-input three-output biquad filter is given in Fig. 7. Current followers used as active elements in filter. Transfer functions of filter are described as:

$$H_{LP} = \frac{I_{LP}}{I_{IN}} = \frac{1}{s^2 R_1 R_2 C_1 C_2 + sR_2 C_2 + 1} \quad (1)$$

$$H_{HP} = \frac{I_{HP}}{I_{IN}} = \frac{s^2 R_1 R_2 C_1 C_2}{s^2 R_1 R_2 C_1 C_2 + sR_2 C_2 + 1} \quad (2)$$

$$H_{BP} = \frac{I_{BP}}{I_{IN}} = \frac{sR_2 C_2}{s^2 R_1 R_2 C_1 C_2 + sR_2 C_2 + 1} \quad (3)$$

A low-pass Butterworth filter with -1dB pass-band of10 kHz and -20 dB stop-band of 15 kHz is realized with the biquad filter given in Fig. 7. Transfer function Butterworth filter, G_{BW} is

$$G_{BW} = \frac{4.6710^6}{s^2 + 26662s + 46710^7} \frac{4.6710^6}{s^2 + 75928s + 46710^7} \frac{4.6710^6}{s^2 + 113635s + 46710^7} \frac{4.6710^6}{s^2 + 134042s + 46710^7} \quad (4)$$

Computed values of each circuit elements to realize Butterworth filter are given in Table 3. Filter is simulated in both AC domain and time domain. AC transfer function using macromodel and element model is given in Fig. 8. For transient analysis, a sinusoidal input with 10μA amplitude and 15 kHz frequency is applied to the input of low-pass filter. Transient response using macromodel end element model is given in Fig. 9.

Simulation times of element model and macromodel are given in Table 4.

Table 3. Element values of biquad filter to build low-pass Butterworth filter

Function	R1	R2	C1	C2
$\frac{4.6710^6}{s^2 + 26662s + 46710^7}$	10kΩ	10kΩ	3.7507nF	0.57092nF
$\frac{4.6710^6}{s^2 + 75928s + 46710^7}$	10kΩ	10kΩ	1.3170nF	1.6259nF
$\frac{4.6710^6}{s^2 + 113635s + 46710^7}$	10kΩ	10kΩ	0.88001nF	2.4333nF
$\frac{4.6710^6}{s^2 + 134042s + 46710^7}$	10kΩ	10kΩ	0.74603nF	2.8703nF

Table 4. Performance table of macromodel versus element model on simulation of Butterworth filter

	AC analysis	Transient analysis
Element model	5.46517 s	23.116 s
Macromodel	0.313 s	1.157 s

5. Conclusions

In this paper, a novel current follower macromodel is proposed. Each element of macromodel is described and related formulas are given. Macromodel is tested in two stages. Firstly, AC and DC test inputs are applied on macromodel circuit and it's shown that both AC and DC responses are very similar to responses of the original follower circuit.

Secondly, macromodel is used realize a Butterworth low-pass filter and simulated in both AC and time domain. According to these simulations, it's obviously shown that macromodel gives very accurate responses in a dramatically short time.

Furthermore, non-linear behavior of macromodel is also satisfactory according to DC responses

6. References

[1] G. Boyle, B. M. Cohn, D. O. Peterson, and J. E. Solomon, "Macromodeling of Integrated Circuit Operational Amplifiers", *in Analog Integrated Circuits*. Selected Reprint Series. IEEE Press, USA, 1978.

[2] H. Kuntman, "Simple and accurate non-linear OTA macromodel for simulation of CMOS OTA-C active filters", *Int. J. Electronics*, 77:993–1006, 1994.

[3] S. Kuta, W. Machowski, and R. Wydmanski, "CMOS current conveyor design and macromodel", *Analog Circuits Design*.

[4] A. Fabre and M. Alami, "A precise macromodel for second generation current conveyors", *IEEE Transactions on Circuits and Systems-I Fundamental Theory and Applications*, 44(7):639–642, July 1997.

[5] N. Tarim, B. Yenen, and H. Kuntman, "Simple and accurate non-linear current conveyor macromodel suitable for simulation of active filters using CCIIs" *Int. J. Circ. Theor. Applic.*, 26:27–38, 1998.

[6] U. Cam, High Performance CMOS FTFN Design and Applications, Doktora Tezi, İstanbul Teknik Üniversitesi Fen Bilimleri Enstitüsü, Maslak,˙ Istanbul, 2000

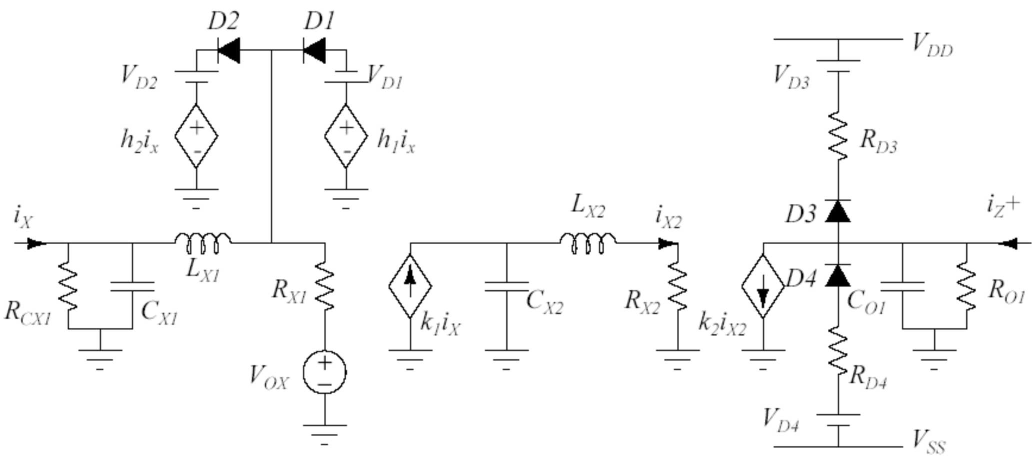

Fig. 2. Proposed macromodel circuit

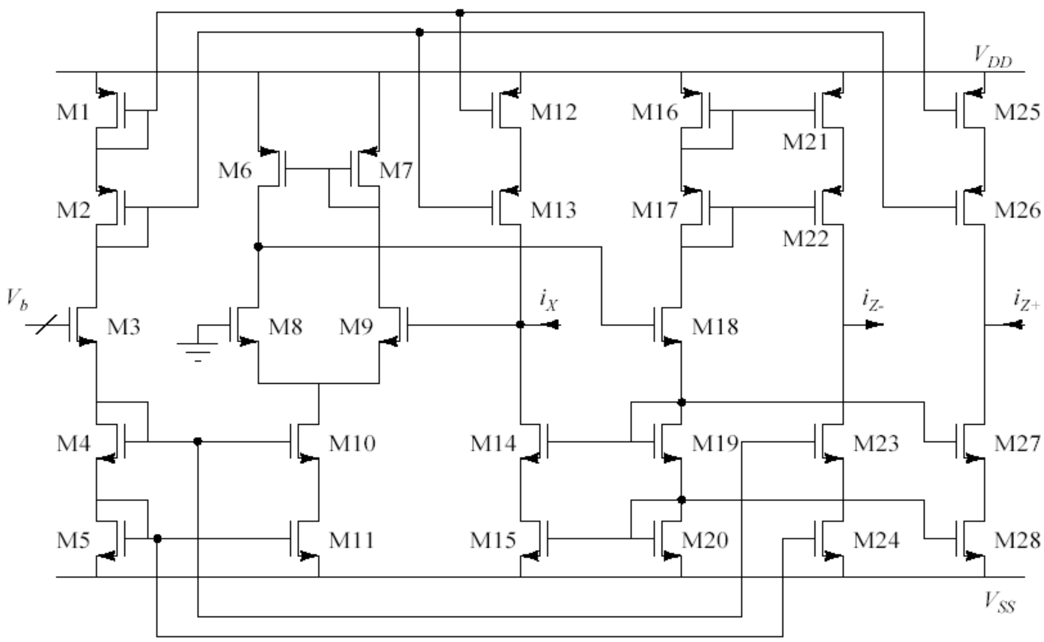

Fig. 3. CMOS current follower circuit

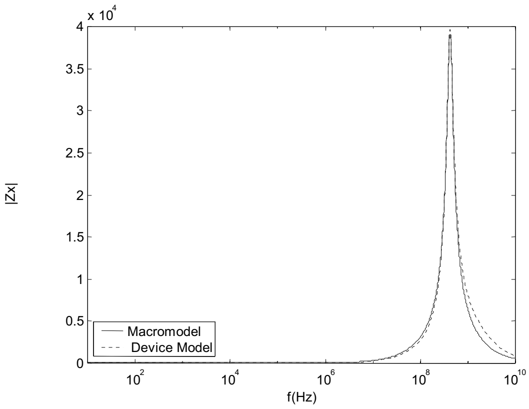

Fig. 4. Input resistance performance of macromodel

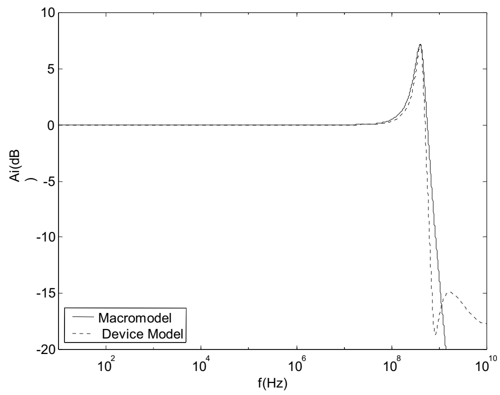

Fig. 5. AC current gain performance of macromodel

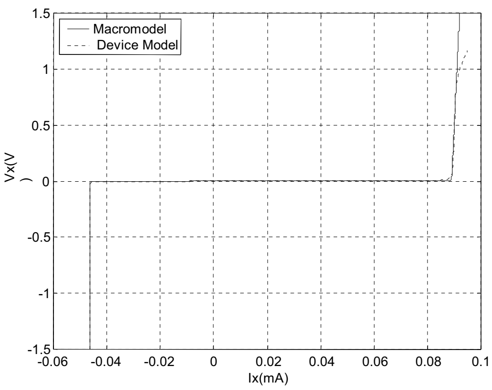

Fig. 6. Voltage-current relation of macromodel at node X

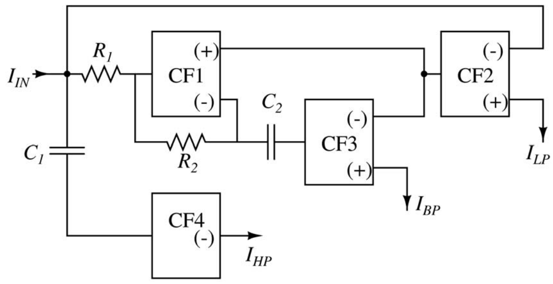

Fig. 7. Current-mode single-input three output biquad filter

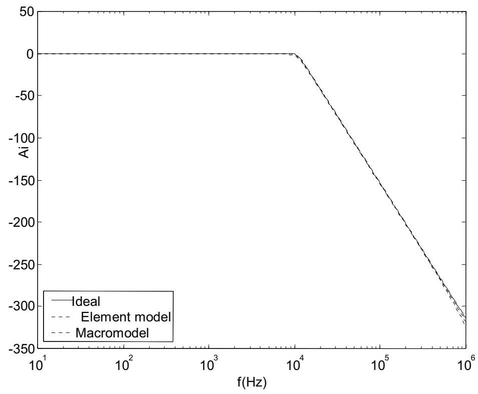

Fig. 8. AC performance of macromodel on Butterworth low-pass filter

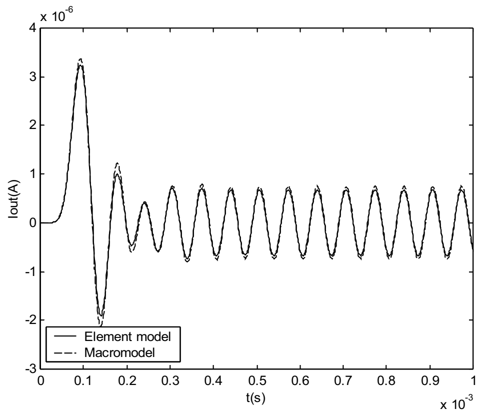

Fig. 9. Macromodel performance on Butterworth low-pass filter