Research Article

Third Order Universal Filter Using Single Operational Transresistance Amplifier

Mourina Ghosh, Sajal K. Paul, Rajiv Kumar Ranjan, and Ashish Ranjan

Department of Electronics Engineering, Indian School of Mines, Dhanbad 826004, India

Correspondence should be addressed to Sajal K. Paul; sajalkpaul@rediffmail.com

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This paper proposes a multi-input single-output (MISO) third order voltage mode (VM) universal filter using only one operational transresistance amplifier (OTRA). The proposed circuit realizes low-pass, high-pass, all-pass, band-pass, and notch responses from the same topology. The PSPICE Simulation results using 0.5 μm CMOS technology agree well with the theoretical design.

1. Introduction

Operational transresistance amplifier (OTRA) has emerged as an alternate current mode analog building block [1, 2] since it inherits all the advantages offered by other current mode building blocks such as current conveyor (CC) [3–6], operational transconductance amplifier (OTA) [7], current differencing buffered amplifier (CDBA) [8], differential voltage current conveyor (DVCC) [9]. The input terminals of OTRA are internally grounded, thereby eliminating parasitic capacitances at the input. OTRA has the advantages of a high slew rate and wide bandwidth. It is a high-gain current input voltage output device. Some analog filters using OTRA have been reported in [10–16] and references cited there in. It is well known that higher order analog filters using different kinds of active elements are of considerable interest, as they may be used for some special applications where sharp cut off is desirable and at the same time also useful to implement digital filters. Higher order filters can be obtained by various methods such as cascading lower order filter or state variable method or signal flow graph. Although OTRA based third order filters are reported in the literature [17–19], they all involve more than one OTRA.

In this work an attempt is made to propose a third order voltage mode (VM) universal filter employing single OTRA as an active element. All of the five filters, namely lowpass (LPF), highpass (HPF), allpass (APF), bandpass (BPF), notch (NF), can be obtained from the same topology.

2. Circuit Description

The circuit symbol of an OTRA is illustrated in Figure 1. The characteristic equations of this element can be described as

$$\begin{bmatrix} V_p \\ V_n \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ R_m & -R_m & 0 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ I_o \end{bmatrix}. \quad (1)$$

A CMOS-based OTRA using 0.5 μm CMOS technology is given in Figure 2 [2].

A generalized n th order filter topology using single OTRA is shown in Figure 3 [20]. The routine analysis gives a voltage transfer function as

$$\frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} = \frac{Y_a - Y_b}{Y_c - Y_d}. \quad (2)$$

The proposed third order universal filter is obtained from Figure 3, if one considers $1/Y_a = Z_a = R_{a1} \parallel 1/sC_{a1} \parallel (R_{a2} + 1/sc_{a2})$, $1/Y_b = Z_b = 1/sC_{b1} \parallel (R_b + 1/sc_{b2})$, $1/Y_c = Z_c = R_c \parallel 1/sC_c$, $1/Y_d = Z_d = R_d \parallel 1/sC_d$ and splits the Y_a terminal into three parts and Y_b terminal into two parts as shown in Figure 4.

The routine analysis gives output voltage as

$$V_{\text{out}} = \frac{N(s)}{D(s)}, \quad (3)$$

FIGURE 1: Block diagram of OTRA.

FIGURE 2: Internal circuit of OTRA [2].

FIGURE 3: Generalized n th order filter.

FIGURE 4: Proposed third order universal filter.

where

$$N(s) = R_c (1 + sC_d R_d) \times \{(1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) V_1 - sC_{a1} R_{a1} (1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) V_2 - sC_{a2} R_{a2} (1 + sC_{b2} R_b) V_3 - sC_{b1} R_{a1} (1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) V_4 - sC_{b2} R_{a1} (1 + sC_{a2} R_c) V_5\}, \quad (4)$$

$$D(s) = R_{a1} (1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) \times \{(1 + sC_c R_c)(1 + sC_d R_d) - sC_d R_c\}.$$

If $C_{a2} R_{a2} = C_d R_d$, then (4) modifies as

$$N(s) = R_c \times \{(1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) V_1 - sC_{a1} R_{a1} (1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) V_2 - sC_{a2} R_{a2} (1 + sC_{b2} R_b) V_3 - sC_{b1} R_{a1} (1 + sC_{b2} R_b)(1 + sC_{a2} R_{a2}) V_4 - sC_{b2} R_{a1} (1 + sC_{a2} R_c) V_5\},$$

$$D(s) = R_{a1} (1 + sC_{b2} R_b) \times \{(1 + sC_c R_c)(1 + sC_d R_d) - sC_d R_c\} = R_{a1} (1 + sC_{b2} R_b) \times \{s^2 C_c R_c C_d R_d + s(C_d R_d + C_c R_c - C_d R_c) + 1\} = R_{a1} [s^3 C_{b2} R_b C_c R_c C_d R_d + s^2 \times \{C_c R_c C_d R_d + C_{b2} R_b C_d R_d + C_{b2} R_b C_c R_c - C_{b2} R_b C_d R_c\} + s\{C_{b2} R_b + C_c R_c + C_d R_d - C_d R_c\} + 1]. \quad (5)$$

The specialization of (4), as shown in Tables 1 and 2, results the transfer function of low-pass filter (LPF), all-pass filter (APF), band-pass filter (BPF), and notch filter (NF) functions. Similarly high-pass (HPF) transfer function is obtained from (4) if $C_{b2} R_b = C_d R_d$.

The natural frequency and quality factor of the proposed circuit for LPF, APF, BPF, NF can be obtained as

$$\omega_0 = \frac{1}{\sqrt[3]{C_c C_d C_{b2} R_c R_b R_d}},$$

$$Q = \frac{\sqrt[3]{C_d C_c C_{b2} R_c R_b R_d}}{C_c R_c + C_d R_d - C_d R_c + C_{b2} R_b - \sqrt[3]{C_c C_d C_{b2} R_c R_b R_d}}, \quad (6)$$

TABLE 1: The availability of each filter response and corresponding selection of V_1, V_2, V_3, V_4 , and V_5 .

Filter response	Inputs V_{in}				
V_{out}	V_1	V_2	V_3	V_4	V_5
Low pass filter (LPF)	1	0	1	0	1
High pass filter (HPF)	0	1	1	0	1
All pass filter (APF)	1	0	1	1	1
Band pass filter (BPF)	0	0	1	0	1
Notch filter (NF)	1	1	1	0	1

and for HPF as

$$\omega_0 = \frac{1}{\sqrt[3]{C_c C_d C_{a2} R_c R_{a2} R_d}},$$

$$Q = \frac{\sqrt[3]{C_d C_c C_{a2} R_c R_{a2} R_d}}{C_c R_c + C_d R_d - C_d R_c + C_{a2} R_{a2} - \sqrt[3]{C_c C_d C_{a2} R_c R_{a2} R_d}}. \quad (7)$$

The sensitivity of ω_0 with respect to passive elements may be expressed as

$$S_{C_c}^{\omega_0} = S_{C_d}^{\omega_0} = S_{C_{b2}}^{\omega_0} = S_{C_{a2}}^{\omega_0} = S_{R_c}^{\omega_0} = S_{R_b}^{\omega_0} = S_{R_d}^{\omega_0} = S_{R_{a2}}^{\omega_0} = -\frac{1}{3}. \quad (8)$$

It shows that the proposed circuit offers low sensitivity.

3. Effect of Nonidealities of OTRA

In this section the effect of finite transresistance gain (R_m) on the output of the filter circuit is considered and for high frequency applications a passive compensation is employed in the same line as of reference [10, 11]. Ideally the transresistance gain is assumed to approach infinity. However, practically R_m is a frequency dependent finite value. Considering the single pole model for the transresistance gain, R_m can be expressed as

$$R_m(s) = \frac{R_0}{1 + s/\omega_0}, \quad (9)$$

where ω_0 is the pole frequency and R_0 is DC transresistance gain. In the case of high frequency application the transresistance gain $R_m(s)$ reduces to

$$R_m(s) = \frac{1}{sC_P}, \quad (10)$$

where

$$C_P = \frac{1}{R_0 \omega_0}. \quad (11)$$

Taking this effect into account the voltage transfer function (2) modifies to

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{Y_a - Y_b}{Y_c - Y_d + sC_P}, \quad (12)$$

FIGURE 5: Frequency response of third order lowpass filter.

FIGURE 6: Frequency response of third order highpass filter.

where sC_P is the uncompensated error term. In the case of high frequency applications, passive compensation method may be employed to account for error introduced in (2) which is given in (11). Inspection of circuit of Figure 4 and denominator of (11) indicates that error term sC_P may be realized by connecting a capacitor C_P in parallel to Y_c or C_c for passive compensation. In other words the value of C_c may be decreased by C_P to absorb the nonideality effect and thus achieving self-compensation. There is another nonideality due to parasitic resistances and capacitances. Since the input nodes in an OTRA are inherently grounded, the effect of parasites are negligible.

4. Simulation Results

The performance of the proposed universal filter is evaluated with CMOS implementation of OTRA as shown in Figure 2 [2], with DC power supply voltages $V_{DD} = -V_{SS} = 1.5$ V and bias voltage $V_B = -0.5$ V. The simulations are performed using PSPICE based on $0.5 \mu\text{m}$ MOSIS (AGILENT) CMOS technology parameters. Aspect ratios used for different transistors are same as [2].

The designed values of resistances and capacitances to obtain multifunction filter output for a cutoff frequency of $f_0 = 200$ KHz and quality factor of $Q = 1$ is shown in Table 3. The simulated frequency responses for gain of LPF, HPF, and BPF are shown in Figures 5, 6, and 7, respectively. It is observed that the simulated values closely

TABLE 2: Condition of realization of each filter.

Filter response	Condition
LPF	$R_c R_{a2} + R_{a1} R_b = R_{a2} R_{a1}, C_{a2} R_{a2} + C_{b2} R_b + C_{a2} R_{a1} = C_{b2} R_{a1}$
HPF	$C_{a1} + C_{a2} = C_{b2}, C_{a1} C_{a2} R_{a2} + C_{a1} C_{b2} R_b + C_{a2} C_{b2} R_b = C_{b2} C_{a2} R_{a2}$
APF	$C_{b1} R_{a1} = C_c R_c, -(C_{a2} R_{a2} + C_{b2} R_b + C_{a1} R_{a1} - C_{b1} R_{a1} - C_{b2} R_{a1}) = C_d R_d + C_c R_c + C_d R_c + C_{b2} R_b, C_{b2} R_b C_{a2} R_{a2} + C_{a2} R_{a1} C_{b2} R_b - C_{b1} R_{a1} C_{a2} R_{a2} - C_{b1} R_{a1} C_{a2} R_b = C_c R_c C_d R_d + C_{b2} R_b C_d R_d + C_{b2} R_b C_c R_c - C_{b2} R_b C_d R_c$
BPF	$C_{a2} = C_{b2}$
NF	$C_{a1} R_{a1} = C_c R_c, C_d R_d + C_{b2} R_b + C_c R_c - C_d R_c = C_{a2} R_{a2} + C_{b2} R_b + C_{a1} R_{a1} + C_{a2} R_{a1} - C_{b2} R_{a1}, C_{b2} R_b C_{a2} R_{a2} + C_{a1} R_{a1} C_{a2} R_{a2} + C_{a1} R_{a1} C_{b2} R_b + C_{b2} R_{a1} C_{a2} R_b = C_{b2} R_{a1} C_{a2} R_{a2}$

FIGURE 7: Frequency response of third order unsymmetrical bandpass filter.

FIGURE 8: Frequency response of third order allpass filter.

FIGURE 9: Frequency response of third order unsymmetrical notch filter.

TABLE 3: Designed values of passive components used for VM third order filters.

Filter response	Component values										
	R_{a1} (k Ω)	C_{a1} (pF)	R_{a2} (k Ω)	C_{a2} (pF)	C_{b1} (pF)	R_b (k Ω)	C_{b2} (pF)	R_c (k Ω)	C_c (pF)	R_d (k Ω)	C_d (pF)
LPF	200	—	200	1.99	—	100	7.96	200	7.96	66.66	5.97
HPF	—	7.96	100	7.96	—	25	15.92	200	7.96	66.66	5.97
APF	200	—	9.52	41.79	7.96	16.66	47.76	200	7.96	66.66	5.97
BPF	—	—	50	7.96	—	100	7.96	200	7.96	66.66	5.97
NF	200	7.96	200	1.99	—	50	15.92	200	7.96	66.66	5.97

FIGURE 10: Variation of %THD with respect to input voltage amplitude.

agree with the theoretical results. Figures 8 and 9 show the frequency responses for both gain and phase for APF and NF, respectively. It is observed that there is deviation of simulated gain at higher frequency for notch filter (NF). To judge the quality of the output, total harmonic distortion is obtained for low-pass, high-pass, and band-pass filter as shown in Figure 10. It is evident that the output distortion is very low and within 0.2% up to 2 volts. Hence it may be claimed that the output is of very good quality and dynamic range is high.

5. Conclusion

An OTRA based universal third order voltage mode filter is presented. Although a number of passive components matching is required, the proposed circuit offers the following advantageous features: (i) use of single OTRA, (ii) it has low output impedance, hence suitable for cascading, (iii) can implement all the five filter function such as lowpass, highpass, bandpass, allpass, and notch from same topology, (iv) moreover all the capacitors are grounded or virtually grounded, so suitable for monolithic IC implementation, and (v) effect of finite transresistance gain can be reduced by self-compensation method, hence no additional elements needed.

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