An Operational Transconductance Amplifier with Multiple–Inputs and a Wide Linear Range

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ABSTRACT

Recently there has been interest in continuous–time Operational Transconductance Amplifier (OTA) filters with characteristics controlled by $g_m C$ products rather than RC products. Advantages of these circuits are simplicity, a low component count, and tunability. A major problem of these circuits has been a limited linear input range. This paper describes a novel OTA design which has a differential input range of nearly 6V and the capability for multiple inputs. The output current is a linear combination of N inputs and the transconductance of each input is controlled by a bias voltage. In addition to design considerations, applications of the multiple–input feature are discussed.

I. Introduction

Recently there has been interest in the use of Operational Transconductance Amplifiers (OTAs) in continuous-time analog filters. A major problem of existing OTAs is that the linear range of the differential input voltage is very limited. In exisiting bipolar OTAs [1], the output current saturates when differential input voltages of more than $\approx$ 30mV are applied. This paper describes a novel OTA design which has a wide linear range and the capability for multiple inputs.

The conventional OTA has an ideal transfer function $I_o = G(V_1 - V_2)$, where the transconductance, G, is controlled by an externally applied dc bias current. It is useful in filter circuits because it is easy to make an integrator by connecting a grounded capacitor to the output node so that $V_o = (\frac{1}{sC})I_o = \frac{G}{sC}(V_1 - V_2)$.

Fig. 1 shows a common second–order OTA filter circuit [2] which has the transfer function

$$\frac{V_o}{V_i} = \frac{G_1 G_2}{s^2 + s\frac{G_1}{C_1} + \frac{G_1 G_2}{C_1 c_2}}.$$

Since the transconductances, G_1 and G_2, are controlled by externally applied bias currents, the characteristics of the filter can be tuned to compensate for component variations and can be time–varying for adaptive applications. This

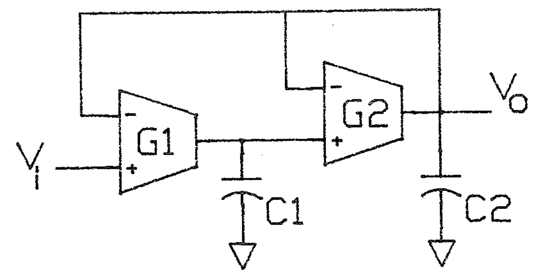

Fig. 1 A 2^{nd} order lowpass OTA filter.

is an advantage over monolithic RC-type circuits because resistor and capacitor values (which are noted for poor absolute accuracy, e.g. resistor variations of $\pm 30\%$), are fixed when the chip is fabricated and they are not easily trimmed. Simplicity and low number of components is another advantage of OTA filters.

The input stage of a conventional OTA is either an emitter coupled or source coupled differential amplifier biased so that both devices are in the high-gain region.

When large differential input voltages are applied, the input stage saturates. This causes distortion and the tail current becomes ineffective at adjusting the small–signal transfer characteristics. The saturation problem can be reduced by using voltage dividers to reduce the signal seen by the differential pair as suggested in the literature, but this approach has significant limitations: an increase in circuit complexity, loading problems in preceeding stages due to the inherent low impedance of the voltage divider, and a possible decrease in the signal to noise ratio. The circuits discussed in the following sections offer alternatives to the high-gain differential amplifier input stage for the OTA.

I. Development

A. The Cascode Circuit

When a MOSFET is biased in its active (ohmic) region the drain current is given by

$$I_d = \beta\left[2\left(V_{gs} - V_T\right) - V_{ds}\right] V_{ds},$$

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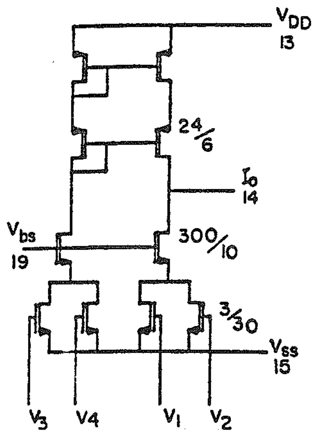

Fig. 5 A four–input cascode OTA. (COTA)

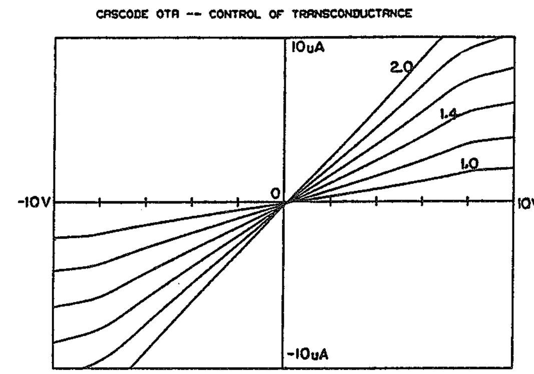

Fig. 6 DC transfer function of the COTA.

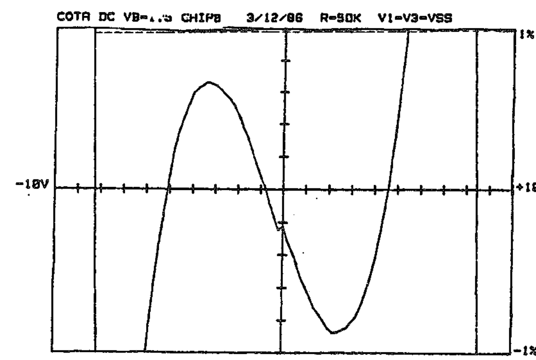

Fig. 7 Linearity error of Fig. 6 for $V_b = 1.5V$.

II. Experimental Results

The circuits discussed in the following paragraphs were fabricated in a double–metal $1.5\mu m$ CMOS process.

A. The Cascode OTA

Fig. 5 shows a multiple–input cascode OTA (COTA) constructed from two multiple-input cascode elements and a current mirror. The DC transfer function for this circuit is given by $I_o = -g_m(V_1 + V_2 - V_3 - V_4)$, where $g_m = 2\beta_1(V_b - V_{T2})$.

The measured DC transfer function $I_{out} vs. V_{diff}$ ($V_{diff} = V_1 - V_3$, and $V_2 = V_4 = V_{SS}$, $V_{DD} = 5V$, $V_{ss} = -5V$) is shown in Fig. 6. The percent nonlinearity for the $V_b = 1.5V$ curve is plotted in Fig. 7 and shows a 1% linear range of $5.5V$ which is much larger than the range available with most existing OTA circuits which have appeared in the literature.

The frequency reponse of this circuit is good. No high–frequency rolloff was observed below 4.5 MHz, the gain–bandwidth of the opamp used in the measurement.

C. Common–Mode–Rejection

The COTA has a common–mode–rejection–ratio, defined by CMRR $= G_{diff}/G_{com}$, of only 40dB which is very poor compared to conventional OTAs. It is not clear yet if this is an inherent problem of this circuit or due to a mismatch in sizes or bias conditions. This limitation will be addressed in a future paper.

III. Applications of the MIOTA

In this section, potential applications of the multiple–input capability of the MIOTA will be discussed.

A. General Summation

In integrated circuits the conventional opamp–resistor summing amplifier may be impractical because of the nonlinearity, poor accuracy, and limited range of values of resistors available in integrated circuits. This is a good application for the MIOTA. The weighting factors can be easily trimmed by the bias control voltages. Although the MIOTA output is a current, this can be readily converted to a voltage, if necessary.

B. Linear Control Circuits

State-variable linear control circuits which generate transfer functions of the form $Q(s) = N(s)/D(s)$ can be constructed using integrators, gain–elements, and summation circuits. [4] The MIOTA is well suited for use in these circuits because it implements all three of these functions.

C. Filters

Many filter circuits can be viewed as simple cases of the basic control circuits. Even in circuits which are not one of these special cases it often happens that two or more OTAs feed current into a common node. Fig. 8 shows 2 second–order multiple–OTA filter circuits (a,c,) from [3] along with implementations using MIOTAs. In particular, note that the general biquad circuit of Fig. 8(d) requires 5 conventional OTAs but only 2 MIOTAs. With separate cascode control voltages, the individual transconductances can all be adjusted independently wheras with common cascode stages, joint control such as is needed for constant-Q ω_o adjustment is possible.

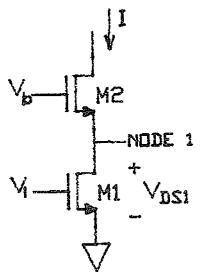

Fig. 2 The cascode transconductance stage.

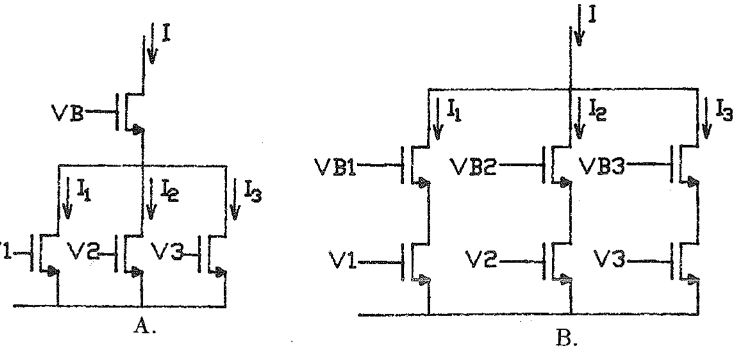

Fig. 3 Connection of transconductance stages for multiple inputs.

where $\beta = \frac{\mu C_{ox} W}{2L}$ and V_T is the threshold voltage. If V_{ds} is held constant, I_d can be written as

$$I_d = (2\beta V_{ds}) V_{gs} - \beta V_{ds} (2V_T + V_{ds}), \qquad (1)$$

or

$$I_d = gV_{gs} + I_{offset}. \qquad (2)$$

where

$$I_{offset} = -\beta V_{ds}(2V_T + V_{ds}).$$

I_d is a linear function of the input voltage V_{gs} and the transconductance is given by

$$g = 2\beta V_{ds}. \qquad (2a)$$

The circuit of Fig. 2, commonly called the cascode configuration, will bias the MOSFET M1 in this way. When M2 is saturated and $W2/L2 \gg W1/L1$, M2 will act to keep V_{ds1} constant. Since $V_{ds1} \approx V_b - V_{T2}$, the transconductance is controlled by the voltage V_b and can be approximated by $g \approx 2\beta(V_b - V_{T2})$. M1 will be biased in the active region when $V_{gs1} > V_{ds1} + V_{T1}$. This gives a potentially large linear range.

Since V_{ds1} is held nearly constant, additional input devices with independent drain current control can be added to the node labled 1 in Fig. 2. The output current, I_o, will be the sum of the individual currents as shown in Fig. 3(a). The circuit of Fig. 3(b) allows for independent weighting of the individual transconductances through the voltage control parameters V_{b1}, V_{b2} and V_{b3}.

In summary, five important characteristics of the cascode circuit of Fig. 2 are (1) a large linear input voltage range, (2) voltage control of the transconductance by the parameter V_b (or V_{b1}, V_{b2}, and V_{b3}), (3) the capability for multiple inputs, (4) high input impedance and (5) high output impedance.

B. Frequency Response

The gate-drain capacitance of a MOSFET in its active region, $C_{gd} \approx \frac{1}{2} WLC_{ox}$, is much larger than the overlap capacitance of a saturated MOSFET. The parasitic capacitance C_{gd1} causes a right–half–plane zero which must be at high frequencies if the circuit is to be stable under negative feedback. The location of this zero is approximated by

$$z_{RHP} = \frac{g_1}{C_{gd1}}, \qquad (3)$$

where g_1 is given by (2a). Substituting gives

$$z_{RHP} = \frac{\mu V_{ds1}}{L_1^2}. \qquad (4)$$

It follows that the length of the input transistor should be kept small so that the RHP zero will occur at a high frequency.

Since good linearity requires $W2/L2 \gg W1/L1$, there is a trade off between linearity, frequency response, and area. If L_1 is small, $W2/L2$ must be large in order to maintain good linearity and the area of M2 may become large.

C. The Multiple–Input OTA Structure

Fig. 4 shows a simple architecture for a multiple–input OTA (MIOTA) constructed using two multiple–input cascode elements and a current mirror. The output current of the device is the difference of the sum of the "+" currents and the "–" currents.[1] When the device is symetric, the offset currents of (2) cancel.

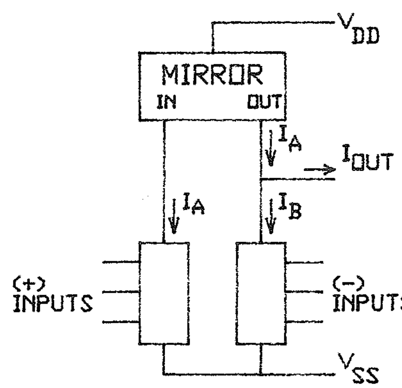

Fig. 4 Block diagram of an OTA.

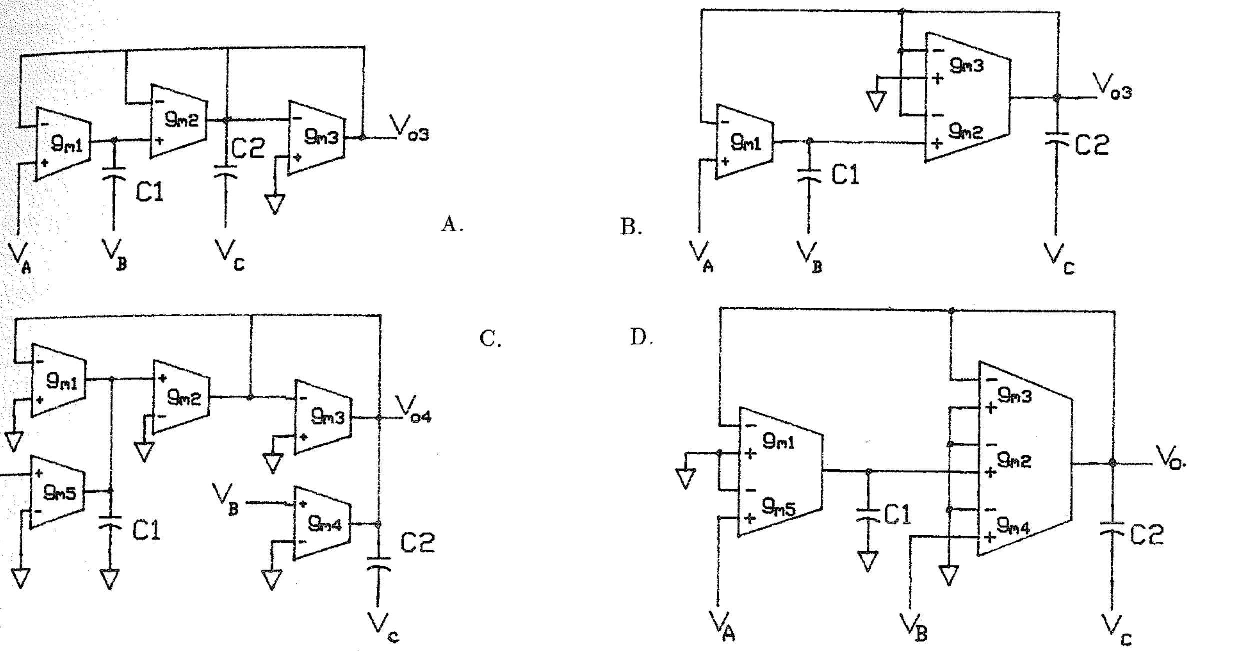

Fig. 8 two MIOTA filter circuits and their conventional equivalents.

D. Discrete Gain Control

Discrete gain control can be achieved by applying the input signal to several inputs via a switching network. A great deal of flexibility is possible depending on the number and weighting of the inputs and how they are switched.

F. Majority Gate Logic

The summation property can also be used to create a form of majority gate logic, —'voting' circuits in which the output value is the value held by the majority of the inputs.

If a MIOTA with an odd number of input pairs is used and all the inverting inputs are tied to a voltage $V_{1/2}$, halfway between logic 1 and logic 0, then the output current will be positive when more of the inputs are 1's and it will be negative when more of the inputs are 0's. Assuming that the output load is capacitive, the output voltage will eventually saturate at the correct logic value.

G. Summary

From the above discussion, it should be apparent that the multiple–input feature of the MIOTA can be implemented functionally by connecting the outputs of several conventional OTAs in parallel. However, for independent control of the transconductances of each input, one conventional OTA is required for each input. In multiple input situations, significant silicon area reductions are possible using the MIOTA. If the structure of Fig. 3(b) is used, each input requires a silicon area of approximately $100 \times 150\mu m$. If the multiple–input structure of Fig. 3(a) is used, the cost of each additional input is just the area of the added input devices. In addition to the multiple input features, the MIOTA offers improved linearity over most conventional OTAs.

IV. Conclusions

An OTA design which addresses the differential input limitation of existing OTAs and has the unique feature of multiple inputs has been presented. Tradeoffs between linearity, area, and frequency response were discussed and applications of the multiple–inputs were considered.

The important advantages of the MIOTA are:

1. a wide linear range; a $5.5V$ range for $\pm 5V$ supplies,
2. multiple inputs; $I_o = \sum_{i=1}^{N} g_i V_i$,
3. voltage control of the transconductance,
4. increased design flexibility due to the multiple–inputs.

The main disadvantages of the MIOTA are:

1. a low CMRR, and
2. interaction of the frequency response and the transconductance.

References

[1] RCA Solid State Division, *Linear Integrated Circuits and MOS/FETs.* New York, New York: RCA Corporation, 1982.

[2] R. L. Geiger and J. Ferrell, "Voltage Controlled Filter Design Using Operational Transconductance Amplifiers," in *IEEE International Symposium on Circuits and Systems,* Newport Beach, CA, May 1983.

[3] R. Geiger and E. Sánchez-Sinencio, "Active Filter Design Using Operational Transconductance Amplifiers : a Tutorial," IEEE Ckts Devices Mag., pp. 20–32, March 1985.

[4] J. J. D'Azzo and C. H. Houpis,it Linear Control System Analysis and Design, Conventional and Modern. New York, New York: McGraw–Hill Inc., 1975.