

Electronic interface for the accurate read-out of resistive sensors in low voltage–low power integrated systems

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Abstract

The accuracy of integrated sensors is often limited by errors of the electronic interface; this is the case in most low voltage–low power integrated sensor systems. In this paper we describe the dynamic op amp matching (DOAM) technique; the circuits using the dynamic op amp matching (DOAMCs) are a new type of circuits using dynamic element matching (DEMCs). In comparison with traditional DEMCs and with chopper circuits, DOAMCs may achieve a *gain enhancement*, while, in comparison with gain enhanced autozero circuits, they offer better noise performance. For these reasons DOAMCs are an attractive strategy for the implementation of accurate electronic interfaces in low voltage–low power integrated sensors; as a design example we present a DOAMC suitable for the read-out of resistive sensors.

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1. Introduction

In most cases, accurate electronic interfaces for sensors require operational amplifiers (op amps) with very high gain and with low input offset and noise voltages; in many practical cases *technological limitations* (that is non-idealities of available devices) and *design constraints* conflict with integration of such op amps.

With reference to *technological limitations*, as an important example, CMOS op amps typically have high input offset and noise voltages. With reference to design constraints, high gain requirements generally conflict with low voltage (limited headroom for transistors makes cascoding techniques problematic) specifications; furthermore low power also requires low biasing currents, resulting in low transconductances, which limits the achievable gain-bandwidth product of amplifiers.

Since *static* compensation techniques may not compensate time-varying errors (such as errors due to noise), *automatic* compensation techniques [1–7] have become very popular in CMOS systems, where, beside the offset voltages, the low frequency input noise voltages of op amps are also not negligible.

Circuits using automatic compensation techniques can be grouped into three main classes: autozero circuits (AZCs), chopper circuits (CHCs) and circuits using dynamic element matching (DEMCs). In previous classifications [1,2] DEMCs and CHCs have been grouped in the same class; however, although some overlap exists between DEMCs and CHCs (that is there are circuits which belong to both the classes), it is better to distinguish between them because their working principles are different [8]. For instance we have recently introduced [8–10] circuits based on dynamic matching of op amps (DOAMCs); DOAMCs are a particular type of DEMCs but they are not CHCs (in particular their accuracy and noise properties are substantially different from those of CHCs); in the same manner CHCs which make use of a purely sinusoidal modulation–demodulation are not DEMCs.

Although it is well known [1] that DEMCs and CHCs have better noise performance than AZCs, it has been believed [1] that, in contrast with AZCs, both DEMCs and CHCs may not achieve *gain enhancement* (that is the compensation of the finite op amp gain). As a consequence, in systems where the gain of op amps may be limited by low voltage–low power specifications, autozeroing has been generally preferred due to its *gain enhancement* capabilities. However we have recently shown [8–10] that properly designed DOAMCs (which are a subset of DEMCs) may

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achieve a significant *gain enhancement*, but having in addition better noise properties (and thus superior accuracy) than AZCs.

Furthermore, DOAMCs do not require high value linear capacitors, which is an important advantage for integration in digital CMOS processes [11–13]; on the other hand DOAMCs require, for low power consumption, high value resistors which could also be not feasible in digital processes where silicide reduces the sheet resistances of both polysilicon and diffusion layers [12,14]. However it is always possible to use an additional mask (with increased costs) in order to selectively block the deposition of silicide on regions needed for the integration of resistors and, in some cases, it could be possible to use well resistors, although their voltage dependence [14] must be taken into account (since it could easily degrade accuracy).

In order to further decrease the power consumption of DOAMCs, if slow operations are acceptable, the analog circuitry could be powered down for large amounts of time.

The dynamic matching of op amps could also improve the performance of the replica-amplifier circuits presented in [15–17] (in those circuits the gain enhancement was limited by gain mismatch), although the simple dynamic op amp matching would not contemporarily lead, in those circuits, to the reduction of the equivalent input offset and low frequency noise voltages.

In this paper we present the dynamic op amp matching principle and we show, as a design example, a new DOAM circuit for the accurate read-out of resistive sensors (such as *strain gauges*); SPICE simulations confirm theoretical expectations.

2. DOAM interface for resistive sensors

2.1. Dynamic op amp matching

Under the (unrealistic) hypothesis of perfect matching of two or more op amps, it is possible, in principle, to design circuits where the errors induced by different op amps compensate each other. The unrealistic matching hypothesis may be removed by dynamic op amp matching, that is the dynamic element matching applied to the op amps. Since the errors induced by op amps comprise, beside the errors due to input offset and noise voltages, also the errors due to the finite gain of the op amps, in principle DOAM makes possible to compensate the finite op amp gain (gain enhancement) without autozeroing.

Clearly, in order to effectively achieve the compensation of both the finite op amp gain and the input offset and noise voltages, it is necessary to design proper circuit topologies (for instance we have already presented elsewhere [3] some circuit topologies for the implementation of accurate buffers, inverting and non-inverting amplifiers using the DOAM).

For simplicity we will refer to DOAM amplifier (buffer, etc.) meaning an amplifier (buffer, etc.) based on dynamic op amp matching.

2.2. Errors of circuits containing op amps

In a given circuit we may define the output voltage error, E_{out} , as the difference between the output voltage and the ideal output voltage. We notice that in a short time interval, T_X , the input noise voltages with frequencies much smaller than $f_X = 1/T_X$ are about constant, so that, within that short time interval, those noise voltages may be regarded as additional input offset voltages [1,2] (in practice T_X is the time required for the single dynamic compensation operation); in the same manner the input offset voltage may be regarded as dc input noise voltage; for these reasons it is often unnecessary to consider contemporarily both the input noise and offset voltages.

In order to determine the errors of circuits containing op amps we can use the following simplified linear model:

$$V_{out} = G(V_+ - V_-) + G_{CM} \left(\frac{1}{2} (V_+ + V_-) \right) + V_{off,out} \quad (1)$$

where G is the differential open loop gain of the op amp, G_{CM} the common mode gain, V_+ and V_- are the voltages at the positive and at the negative input terminals, $V_{off,out}$ is the output offset voltage; for simplicity we assume all other components (but op amps) ideal.

2.3. Classic and DOAM interface for resistive sensors

In order to read out the variation of the resistance of a resistive sensor it is often convenient to transform such variation into a voltage variation and, therefore, an interface for resistive sensors generally comprise a *resistance variation to voltage converter*.

A classic *resistance variation to voltage converter* is shown in Fig. 1, where R_{2S} is the sensor resistance and is given by

$$R_{2S} = R_2 + \Delta R \quad (2)$$

In case of ideal op amp the output voltage would be

$$V_{out} = -V_{REF} \frac{\Delta R}{R_1 + R_2} \quad (3)$$

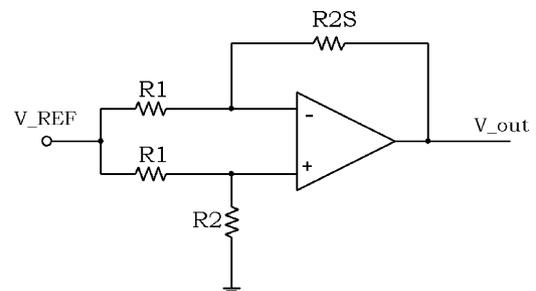


Fig. 1. Classic interface for resistive sensors.

However, if we consider the simplified linear model (1) for the op amp we may write the following equations:

$$V_{out} = G(V_+ - V_-) + G_{CM} \left(\frac{V_+ + V_-}{2} \right) + V_{off,out},$$

$$V_+ = \frac{V_{REF} R_2}{R_1 + R_2}, \quad \frac{V_{out} - V_-}{R_2 + \Delta R} = \frac{V_- - V_{REF}}{R_1},$$

$$E_{out} = V_{out} - V_{out,ideal} = V_{out} - \left(-V_{REF} \frac{\Delta R_2}{R_1 + R_2} \right) \quad (4)$$

We may solve this linear system, obtaining

$$E_{out} = 2V_{off,out} \frac{R_1^2 + R_2^2 + (R_1 + R_2)\Delta R + 2R_1 R_2}{R_1^2(2G - G_{CM} + 2) + R_1 R_2(2G - G_{CM} + 4) + 2R_2^2 + 2(R_1 + R_2)\Delta R}$$

$$+ 2V_{REF} \frac{R_2^2 G_{CM} + (R_1 + R_2)\Delta R + R_2 G_{CM} \Delta R + R_1 R_2 G_{CM} + (\Delta R)^2}{R_1^2(2G - G_{CM} + 2) + R_1 R_2(2G - G_{CM} + 4) + 2R_2^2 + 2(R_1 + R_2)\Delta R} \quad (5)$$

Effects of the input offset and low frequency noise voltages of the op amp may be strongly reduced by applying proper dynamic matching or chopper techniques; nevertheless the output voltage error of the circuit would still be approximately (if we consider the dominant term in the denominator) inversely proportional to the differential open loop gain of the op amp, G , which could be unacceptable if G is not very high.

Fig. 2 shows a more complex *resistance variation to voltage converter* (requiring two resistive sensors, two op amps and, roughly, double power consumption and double area). If the compensation resistors R_A , R_B , R_C and R_D are sized according to the design rules

$$R_A = R_B = 2R, \quad R_C = R_D = R \quad (6)$$

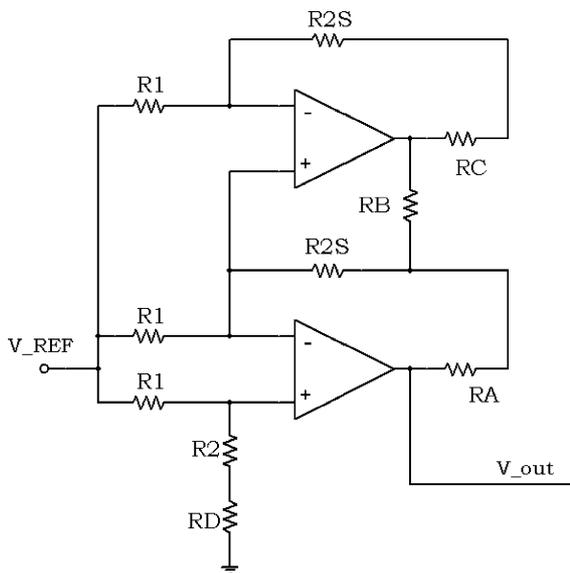


Fig. 2. DOAM interface for resistive sensors (the op amps must be dynamically matched).

this circuit would produce, in case of ideal op amps, an output voltage equal to

$$V_{out} = -V_{REF} \frac{\Delta R_{2S}}{R_1 + R_2 + R} \quad (7)$$

However, if we consider the simplified linear model (1) and ideally matched op amps (the mismatch may be strongly reduced by dynamic amp matching) we find that the output voltage error is approximately inversely proportional to G^2 (we do not report here the long analytical expressions of the output voltage error).

In order to satisfy the design rules (6) and in order to accurately set the sensitivity of the *resistance variation to voltage converter*, all the resistors R_1 , R_2 , R_A , R_B and R_C and the sensor resistors must be of the same type and properly laid out; in some applications it could be useful to (contemporarily) apply the dynamic element matching also to the resistances in order to make their ratios as accurate as possible (see [5]).

Fig. 3 shows a DOAM differential amplifier (even in this case the compensation of both the finite op amp gain and the input offset and noise voltage requires that the op amps are dynamically matched by switches not shown in the figure).

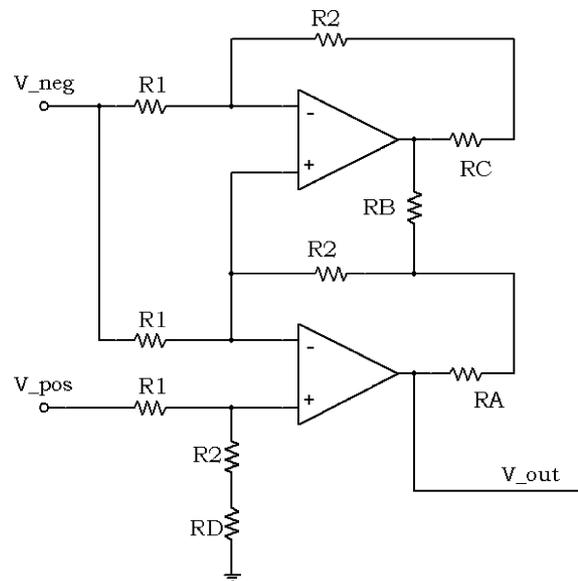


Fig. 3. DOAM differential amplifier (the op amps must be dynamically matched).

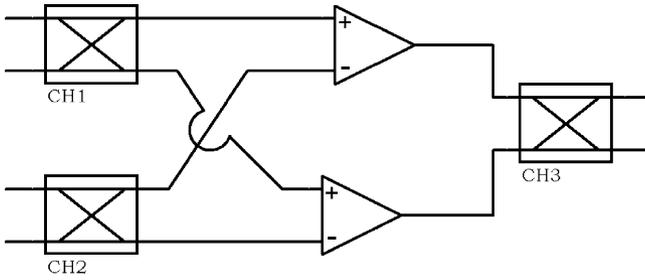


Fig. 4. Chopper switches for the dynamic matching of the op amps.

2.4. Chopper switches for the dynamic op amp matching

As we have already discussed, in practical circuits it is necessary to dynamically match the op amps; this may be done by using chopper switches as shown in Fig. 4 (chopper switches are two ports networks constituted by switches connected in such a way that the “straight” connections are enabled in a first phase and the “cross” connections are enabled in the second phase). Chopper switches are easily implemented in CMOS circuits by pass transistors; in traditional dynamic element matching and chopper circuits it is generally convenient to use minimum size transistors in order to reduce errors caused by the overlap capacitances C_{GS} and C_{GD} (clock feedthrough [1]).

However, in dynamic op amp matching circuits an additional issue must be considered. The parasitic resistances of the CMOS switches are in series with the input terminals of the op amps (and thus there is very little current across such switches) or they are in series with the output of the op amps (and therefore, if the switches are properly placed, the errors due to parasitic resistances are reduced by the feedback); nevertheless, since dynamic op amp matching is proposed for relatively low gain op amps, the reduction of the equivalent output resistance achieved by feedback would be less effective. As a result, the pass transistors in series with the output of the op amps must be properly sized (increasing their width reduces the parasitic resistance but also increases the overlap capacitances C_{GS} and C_{GD}).

2.5. Input equivalent noise of DOAM interface for resistive sensors

In practical circuits the op amp must be dynamically matched; the simple dynamic op amp matching will automatically compensate, in the circuit shown in Fig. 2, both the input offset and low frequency (i.e. at frequencies much below the “interchanging” frequency) noise voltages.

In case of CHCs using switches for the modulation–demodulation we have, as discussed in [1]

$$\tilde{V}_{n,\text{chopper}}(t) = \tilde{V}_n(t) m(t) \quad (8)$$

where the symbol “ \sim ” is used to distinguish random processes, $\tilde{V}_{n,\text{chopper}}(t)$ is the equivalent input noise voltage of

the chopper amplifier, $\tilde{V}_n(t)$ is the input noise voltage of the original amplifier and

$$m(t) = \begin{cases} 1, & (2n-1)T_0 \leq t < 2nT_0, \quad n \in \mathbb{Z} \\ -1, & 2nT_0 \leq t < (2n+1)T_0, \quad n \in \mathbb{Z} \end{cases} \quad (9)$$

In order to study the noise performance of the DOAM interface for resistive sensors shown in Fig. 2, it is convenient to consider an infinite open loop op amp gain so that the input voltage error is given by the input offset and noise voltage; for simplicity we do not explicitly consider the input offset voltage (which may be regarded as a dc input noise voltage); furthermore, since the circuit is constituted by linear components (the op amp is assumed linear for simplicity) we may use the superposition of effects.

We may then consider a zero reference voltage and compute the output noise voltage (that is the output voltage originated by the noise) when the *op amps are not interchanged* (for simplicity we consider random processes which simply add each other). By inspection of the circuit we may write the following linear equations

$$\begin{aligned} \tilde{V}_{-,1} &= \tilde{V}_{n,1}, & \tilde{V}_{-,2} &= \tilde{V}_{n,1} + \tilde{V}_{n,2}, \\ \tilde{V}_X &= \tilde{V}_{-,1} \frac{R_2 + R_1 + \Delta R}{R_1}, \\ \tilde{V}_{n,\text{out},2} &= \tilde{V}_{-,2} \frac{R_2 + R_1 + R + \Delta R}{R_1}, \\ \tilde{V}_{n,\text{out},1} &= \tilde{V}_X + (\tilde{V}_X - \tilde{V}_{-,1}) \frac{2R}{R_2 + \Delta R} + (\tilde{V}_X - \tilde{V}_{n,\text{out},2}) \end{aligned} \quad (10)$$

where $\tilde{V}_{n1}(t)$ and $\tilde{V}_{n2}(t)$ are the equivalent input noise voltages of the two op amps.

It is then possible to find the output noise voltage (random process) $\tilde{V}_{n,\text{out},1}$

$$\tilde{V}_{n,\text{out},1} = (\tilde{V}_{n,1} - \tilde{V}_{n,2}) \frac{R_1 + R_2 + R + \Delta R}{R_1} \quad (11)$$

If we consider the classic *resistance variation to voltage converter* shown in Fig. 1 we obtain

$$\tilde{V}_{n,\text{out}} = \tilde{V}_n \frac{R_1 + R_2 + \Delta R}{R_1} \quad (12)$$

As a result the output noise voltage produced in the DOAM circuit is (approximately) the same output noise voltage which would be produced by an equivalent input noise voltage

$$\tilde{V}_{n,\text{in}}(t) = \tilde{V}_{n1}(t) - \tilde{V}_{n2}(t) \quad (13)$$

in the classic circuit.

Since the random processes $\tilde{V}_{n1}(t)$ and $\tilde{V}_{n2}(t)$ are uncorrelated and have the same (nominal) spectral power density, we may write for the root mean squares (no matter which is the bandwidth of interest)

$$\begin{aligned} V_{\text{rms},n,\text{in}} &= \sqrt{V_{\text{rms},n1}^2 + V_{\text{rms},n2}^2} = \sqrt{V_{\text{rms},n}^2 + V_{\text{rms},n}^2} \\ &= \sqrt{2} V_{\text{rms},n} \end{aligned} \quad (14)$$

By considering (13) it is evident that, *if the two op amps are dynamically interchanged (with period T_0)*, the equivalent input noise voltage of the DOAM non-inverting voltage amplifier is

$$\tilde{V}_{n,\text{DOAM}}(t) = \tilde{V}_{n,\text{in}}(t) m(t) = [\tilde{V}_{n1}(t) - \tilde{V}_{n2}(t)] m(t) \quad (15)$$

so that the input equivalent noise rms voltage of the DOAM non-inverting voltage amplifier is $\sqrt{2}$ times the correspondent voltage of a “correspondent” chopper circuit using switches for modulation/demodulation (see [1] for the noise analysis of this kind of circuits and of autozero circuits). We mention that the same result also holds for the DOAM non-inverting amplifier, inverting amplifier and buffer presented in [8,9].

In conclusion, in comparison with traditional circuits using dynamic element matching and with chopper circuits, DOAMCs may achieve a strong gain enhancement, but at the cost of higher noise (the equivalent input noise RMS voltage is $\sqrt{2}$ times higher), larger area (about doubled) and power consumption (about doubled). However these costs could be affordable in many low voltage–low power systems because of the very large gain enhancement that may result from dynamic op amp matching.

On the other hand, in comparison with gain enhanced AZCs (see [1]), DOAMCs may achieve a similar gain enhancement but having better noise performance (because there is no sampling), thus leading, in principle, to superior accuracy performance in low voltage–low power CMOS systems. We stress that in our analysis we did not consider the noise generated by the feedback resistors; such resistors are necessary in DOAMCs and should be high valued for low power consumption; nevertheless in many practical cases the noise generated by CMOS transistors will dominate the residual noise.

2.6. Simulations

Experimental results on the DOAM non-inverting amplifier have been presented in [9].

In [8,9,18,19] we have reported the theoretical analysis and SPICE simulations of the effectiveness of the DOAM in the compensation of the mismatch between different op amps.

Here we only present SPICE simulations of the new circuit topology for the read-out of resistive sensors.

For simplicity the two op amps have been replaced by two ideal single ended differential amplifiers where an ideal single ended differential amplifier is defined as a two ports network having:

- an output voltage given by the input voltage multiplied by the gain of the differential amplifier,
- a zero input current,
- the negative terminal of the output port grounded.

We define the *resistance variation error* as the error in the estimation of the variation of the sensor resistance, ΔR . If

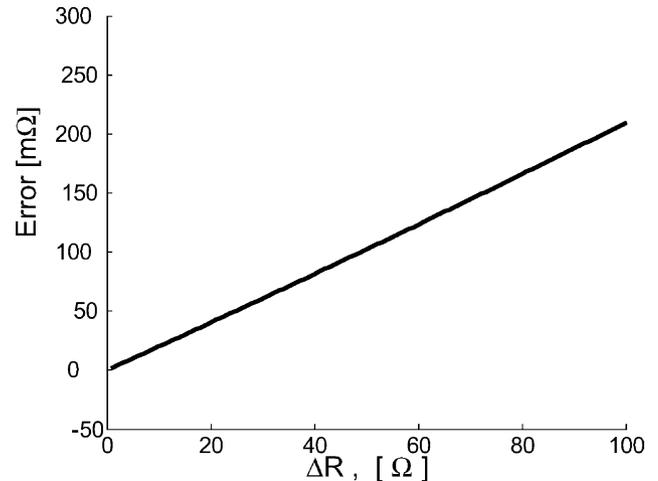


Fig. 5. The resistance variation error vs. the variation of the sensor resistance in the classic interface for resistive sensors.

we consider the classic circuit topology, with a voltage gain of the op amp equal to 1000 and $R_1 = R_2$, the resistance variation error is shown in Fig. 5 as a function of ΔR .

The solid line in Fig. 6 shows the resistance variation error for the DOAM circuit in the case of ideal op amp matching (voltage gain equal to 1000 for both the op amps). The typical mismatch of the differential gains of nominally identical op amps (integrated within the same chip and thus experiencing about the same temperature, supplied by the same voltages, etc.) is in the order of 10% in normal operative conditions. The dashed line in Fig. 6 shows the resistance variation error, after dynamic op amp matching, in the case of two op amps having their voltage gains equal to, respectively, 1000 and 900 (10% mismatch).

We also mention that, in order to achieve the best offset reduction it is better to use a four phases clock strategies, so that we may also exchange the input transistors of each op amps [8].

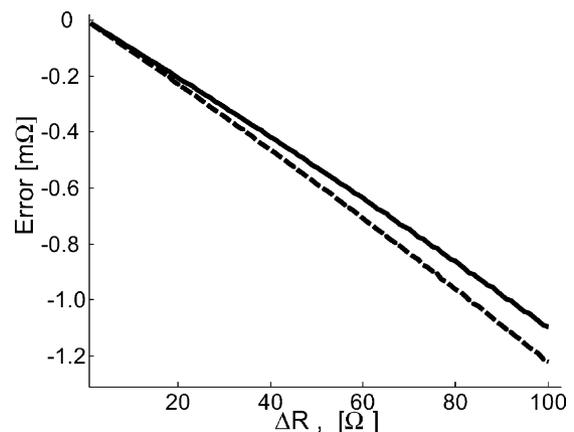


Fig. 6. The resistance variation error vs. the variation of the sensor resistance in the DOAM interface for resistive sensors; the solid line shows the error when the gain of both the op amps is equal to 1000 (ideal matching); the dashed line shows the residual error (after dynamic op amp matching) when the gains of the two op amps are 1000 and 900 (10% mismatch).

3. Conclusions

In low voltage–low power CMOS systems it may be very important to reduce both the errors due to the input offset and noise voltages of op amps and the errors due to their finite gains. The circuits using dynamic op amp matching are the first ever reported circuits which may achieve a reduction of both the aforementioned errors without autozeroing, resulting in better noise performance and therefore in superior accuracy. Furthermore DOAMCs allow continuous time operations and do not require high valued linear capacitors (in contrast with gain enhanced autozero circuits), although, for low power consumption, they require high resistor values.

In this paper we have presented a DOAM interface for the read-out of resistive sensors; the dynamic op amp matching allows to compensate the input offset and noise voltages and the finite op amp gains; SPICE simulations confirm theoretical expectations.

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Biographies

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