Introduction

For many animals, smell can easily rank as the most important sense; the most discriminating sense and the sense on which survival mostly depends – while in humans the sense of smell is probably the least appreciated of the five senses (Neaves and Hatfield, 1995). However, the human sense of smell is still a valuable tool in numerous industries. Trained panels of experts, supported by gas chromatography and mass spectrometry are extremely useful in quantifying and benchmarking of odours. But these techniques are expensive, slow and generally unsuitable for performance in the field (Nagle et al., 1998). Hence, the need is clear for these methods to be improved upon, or perhaps to be replaced with an alternative solution, which accommodates portability, real-time performance and of course, provides the required level of odour discrimination. The “electronic nose” may just provide such a solution.

The electronic model of the olfactory system

The electronic nose draws its inspiration from the biological olfactory system. It is made up of roughly three parts, which have their equivalents in the biological system:

1. the sensor array,
2. the signal conditioning and data pre-processor and
3. the pattern recognition (PARC) engine (Craven et al., 1996) is shown in Figure 1.

In the electronic nose system, odorant molecules induce changes in the physical/chemical properties of the sensor array (Shurmer and Gardner, 1992). Using an appropriate interface circuit, these changes are represented as an analogue signal. This signal may be amplified, filtered, offset, linearised, compensated for temperature dependency and digitised before being fed into the pattern recognition system as shown in Figure 2.

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Chemoresistive sensors for electronic nose applications

Gas sensors form the individual elements of the electronic noses’ sensor array. There are many types of gas sensor suitable for odour classification. Chemoresistors are widely used in the construction of arrays for gas and odour measurements (Pearce et al., 2003a). Due to a chemical reaction, conductivity changes are induced in the sensing material upon interaction with gaseous/odorant molecules. As the focus of this review is on front-end signal conditioning circuits for odour sensitive chemoresistors, a brief introduction to this category of sensor follows.

Metal-oxide sensors

In oxide based sensing materials, odorant molecules induce reversible changes in conductivity by reacting with chemisorbed oxygen species. These sensors require heating elements, as they operate at elevated temperatures (100-600°C) (Gardner and Bartlett, 1994). These high temperatures enhance the sensing mechanism, i.e. facilitate the adsorption and desorption of gaseous components at the sensor surface. Metal-oxide thin films are usually deposited using sputtering techniques, which allows for good sensor reproducibility. Thick film versions are also achievable; however, in the thick film versions the oxide layer is less permeable, thus limiting diffusion of oxide components into the oxide bulk (Corcoran, 1993). These sensors are very sensitive to combustible gasses, alcohols and volatile matter from foodstuffs (Shurmer, 1990), but are generally poor at detecting sulphur- or nitrogen-based odours (Gardner and Bartlett, 1994). Figure 3 shows the typical layout of a metal-oxide based chemoresistor.

Electroconducting polymer sensors

In recent years, considerable attention has been paid to the use of arrays of chemoresistors based on conducting-polymer sensors.

Figure 3 The general layout of a conductivity sensor. The active material is a conducting polymer or metal oxide. The heater, used only for metal-oxide, is normally a platinum metal trace or wire.
films. (Dyer and Gardner, 1997). These materials are prepared by the electrochemical polymerisation of monomers. The main types of materials used in the fabrication of such devices include pyrroles, anilines and biological lipid coatings (Gardner and Bartlett, 1994; Shurmer and Gardner, 1992). Polymers may be prepared both electrochemically and chemically in a range of soluble and insoluble forms (Partridge et al., 2000). The active material used in the device of Figure 3 is a conducting polymer from families such as the polypyrroles, thiophenes, indoles or furans. In order to use these polymers in a sensor device, microfabrication techniques are employed to create electrodes. Then the conducting-polymer is electropolymerised between the electrodes by cycling a voltage between them. Varying voltage sweep rate and a series of polymer precursors when applied yield a wide variety of active materials (Nagle et al., 1998). Typically, these devices can operate at room temperature (20-60°C). A reversible change in resistance is observed in the polymer upon exposure to different gasses. They are responsive to a wide variety of odours but are generally low on sensitivity (Craven et al., 1996).

Conducting-polymer chemoresistors are of increasing importance in the field of gas sensing, due to their ease of fabrication and ability to operate without a heating element (Cole et al., 2001). However, certain characteristics of these sensors present challenges for the front-end interface circuitry.

Conducting-polymer sensors are relatively low on sensitivity when compared to metal-oxides, exhibiting typical resistive changes of 1 per cent at ppm concentrations (Dyer and Gardner, 1997); hence, a circuit with a high sensitivity is required.

These sensors may also exhibit long-term drift effects. However, this phenomenon can be tolerated to some degree because the important parameter to be monitored is the fractional resistance change and this tends to remain constant for a given odour (Harris et al., 1997).

Reproducibility is an issue in the fabrication of conducting-polymer sensors, hence, the interface circuit must cope with large batch-to-batch variations in baseline resistance (10Ω-100kΩ) (Cole et al., 2001). Due to this lack of reproducibility, manufacturing similar arrays of these sensors presents major difficulties. Reproducibility of response may also be very difficult to achieve in arrays of such sensors. Hence, very flexible calibration and pattern recognition tools are required (Bicego et al., 2002). Moreover, in large arrays of sensors of one class, sensors that may not contribute information always contribute noise (Stetter et al., 2000).

Furthermore, conducting-polymer films possess a large temperature coefficient of resistance (∼ ~ 10^2°C) (Cole et al., 2001). Due to this large temperature coefficient of resistance it must be ensured that unintentional self-heating of the conducting-polymer sensor be avoided; it has been shown that the thinnest films must be probed at powers below a milliwatt to prevent heating during measurement (Harris et al., 1997).

Then, it is clear that in the successful design/selection of a front-end signal conditioning circuit for the interrogation of conducting-polymer chemoresistors, most, if not all of the sensor limitations must be addressed so as to extract the most useful information, and to decrease the required amount of subsequent signal processing.

Front-end signal conditioning circuits used in electronic nose systems

The overall performance of the electronic nose system will depend on the individual performance of its constituent elements. Although often overlooked, it is clear that careful design/selection of the front-end signal conditioning circuit is critical if optimal performance of the odour sensing system is to be achieved (Pearce et al., 2003d).

Front-end signal conditioning for an electronic nose system may typically perform a number of the following important functions: sensor biasing, multiplexing of array output signals, linearisation, amplification, offset control, and temperature compensation (Baltes et al., 1998; Horn, 1997).

The type of signal conditioning circuit for an electronic nose system is dependent on the type (or types) of sensor employed (Neaves and Hatfield, 1995) and should be designed in such a way that the maximum amount of information is acquired from the sensor (Corcoran, 1993).

In the following sections, various circuits, which have been employed as front-end signal conditioners for chemoresistor-based sensor arrays, are presented and analysed.
The potential divider

Forming a potential divider circuit from a chemoresistor sensor device and a reference resistor is the conventional method of converting a resistance change into an electrical signal (Shurmer et al., 1993). Shurmer and Gardner (1992) have made use of the potential divider methodology for the interrogation of chemoresistors in the past, and it is the interface circuit recommended by several metal-oxide sensor manufacturers (Pearce et al., 2003c). Figure 4 shows a potential divider circuit, the output of which is fed into a voltage-follower of unity gain. Changes in sensor resistance result in voltage changes across the sensor (or a load resistor). For the potential divider circuit of Figure 4 the output voltage \( V_{\text{OUT}} \) is related to the sensor resistance \( R_S \) by:

\[
V_{\text{OUT}} = \frac{V_{\text{IN}} R_S}{R_S + R_1}
\]  

The sensitivity of the potential divider is given by:

\[
S = \frac{\partial V_{\text{OUT}}}{\partial R_S} = \frac{V_{\text{IN}} R_1}{(R_S + R_1)^2}
\]  

From equation (2) it can be seen that \( R_1 \) is a component in the sensitivity equation, hence the value of \( R_1 \) should be chosen such that the sensitivity is maximised. It can be shown that the sensitivity is maximised when \( R_1 \) is chosen equal to the baseline resistance of the sensor.

The sensor resistance, \( R_S \), will now be mathematically defined. \( R_S \) can be expressed in terms of \( R \) and \( \beta \), where \( R \) is the baseline resistance of the sensor and \( \beta \) represents the fractional change in \( R \) in the presence of an odorant gas. Hence, \( R_S \) is given by the expression:

\[
R_S = R + \Delta R = R(1 + \beta)
\]  

where \( \beta = \Delta R/R \), and \( \Delta R \) is the change in resistance due to an odorant.

Figure 5 displays the behaviour of the output signal for the potential divider circuit of Figure 4 for a wide range of \( \beta \).

The non-linear relationship between the output voltage and sensor resistance for the constant-voltage potential divider circuit (Figure 4) is evident in the plot of Figure 5. To quantitatively assess the performance of all of the interface circuits presented, they are all assessed using a specific test case. It is attempted to mathematically derive a value for the maximum sensitivity achievable for each circuit arrangement with regard to interfacing to a thin-film conducting polymer sensor.

Test case analysis for constant-voltage potential divider

Let the baseline resistance of the conducting polymer sensor assume the typical value of 10 kΩ (Dyer and Gardner, 1997).

\[
R = 10 \text{ kΩ}
\]  

The power \( P_S \) dissipated in the sensor is given by the equation:

\[
P_S = \frac{V_S^2}{R_S}
\]

where \( V_S \) is the voltage across the sensor.

Re-arranging equation (5), we get an expression for the voltage across the sensor:

\[
V_S = \sqrt{P_S R_S}
\]

By re-arranging equation (1) we obtain an expression for the excitation voltage \( V_{\text{IN}} \) in

Figure 4 A constant voltage potential divider circuit with buffer amplifier

Figure 5 A plot of the output voltage against fractional resistance change (\( \beta \)) for the constant-voltage potential divider circuit \( (V_{\text{IN}} = 10 \text{ V}, R_1 = R) \)
terms of the output voltage \( V_{\text{OUT}} \) and the resistances \( R_S \) and \( R_1 \):

\[
V_{\text{IN}} = V_{\text{OUT}} \left( 1 + \frac{R_1}{R_S} \right) \quad (7)
\]

In this case \( V_{\text{OUT}} = V_S \); hence, from equations (6) and (7), an expression is obtained for the excitation voltage of the potential divider circuit in terms of the power dissipated in the sensor:

\[
V_{\text{IN}} = \left( 1 + \frac{R_1}{R_S} \right) \sqrt{P_S R_S} \quad (8)
\]

It is known that the power dissipated in the thinnest conducting-polymer films must be kept below 1 mW (Harris et al., 1997). Let the maximum power that can be dissipated by the sensor be 1 mW \( (P_{\text{Smax}} = 1 \text{ mW}) \) and \( R_1 = R_S = R \), a value for the maximum excitation voltage is calculated from equation (8) as:

\[
V_{\text{IN max}} = 6.32 \text{ V} \quad (9)
\]

Using equation (2) we can now obtain a value for the maximum sensitivity achievable by this circuit when presented with the task of interfacing to the thin-film conducting-polymer sensor proposed:

\[
S_{\text{MAX}} = 0.158 \text{ mV/} \Omega \quad (10)
\]

The constant-current potential divider
As it can be observed from equation (1) and the plot of this equation over a certain range of \( \beta \) (Figure 5), there is a non-linear relationship between the sensor resistance and the output voltage for the constant-voltage potential divider. For many sensing applications this non-linearity proves to be an undesirable characteristic. To address this non-linearity the excitation voltage \( V_{\text{IN}} \) is replaced with a constant-current source \( I_{\text{IN}} \). Figure 6 shows a potential divider circuit with a constant current power supply.

The output voltage for this arrangement is defined as:

\[
V_{\text{OUT}} = I_{\text{IN}} R_S \quad (11)
\]

From equation (11), it can be seen that the output voltage is dependent on the sensor resistance only; \( R_1 \), or any change in \( R_1 \), does not influence the output voltage. Hence, it is possible to eliminate \( R_1 \) from the circuit and construct a simplified circuit as shown in Figure 7.

It can be observed from the plot of Figure 8 that the output voltage of the constant-current potential divider is a linear function of the sensor resistance. This linearity lends itself to odour sensing applications, because the subsequent amount of signal processing is reduced if output signals received from the interface circuit are linear functions of gas concentration. Furthermore, it has been found that for low gas concentrations.
(<100 ppm), the principle of superposition holds, i.e. the combined effects of two or more gases in an analyte mixture result in a sensor response which is additive (Shurmer, 1990), hence, the output signal for a circuit with a linear characteristic will be additive also.

The sensitivity of the constant-current potential divider is derived as:

\[
S = \frac{\Delta V_{OUT}}{\Delta R_S} = I_{IN}
\]  

(12)

It can be seen from equation (12) that the sensitivity is constant and equal to the current flowing in the circuit. Hence, the sensitivity can be increased simply by increasing the supply current – of course, there is a limit to the current that can be passed through the sensor.

The constant-current potential divider will now be assessed using the same test case as the constant-voltage potential divider, i.e. assessed on the basis of the maximum sensitivity achievable when interfacing to the thin-film conducting-polymer sensor previously proposed.

Test case analysis for constant-current potential divider
The power \(P_S\) dissipated in the sensor is given by the equation:

\[
P_S = I_S^2 R_S
\]  

(13)

Rearranging equation (13) we obtain an expression for the sensor current:

\[
I_S = \frac{P_S}{R_S}
\]  

(14)

From the parameters specified by the test case, the maximum current calculated is:

\[
I_{S\text{MAX}} = 0.316 \text{ mA}
\]  

(15)

But \(I_{S\text{MAX}} = I_{IN\text{MAX}}\); hence, from equation (12) the maximum sensitivity is calculated as:

\[
S_{\text{MAX}} = 0.316 \text{ mV/Ω}
\]  

(16)

Comments on potential dividers
Potential dividers are simple circuits to implement; however they have numerous inherent disadvantages. Firstly, they are not very sensitive to small changes in (sensor) resistance – see equations (10) and (17).

It has been stated by Shurmer et al. (1993) that a profound limitation is placed on sensitivity, when the dominant component of the sensor output signal is due to sensor resistance in the absence of odour (baseline resistance), and the minor component due to the change in resistance caused by the presence of odorant molecules – such is the case with the potential divider circuit. Secondly, for constant-voltage potential divider, the output signal is non-linear – especially, when the resistance change is large.

Thirdly, the output signal is also dependent on the temperature dependency of the sensor itself. However, a degree of temperature compensation can be achieved in the constant-voltage potential divider circuit if the reference element is a passivated copy of the sensing element, i.e. it has the same temperature dependence but blind towards the measurand (Gardner, 1994). The use of a passivated sensing element, which is closely matched to the active sensor can also compensate for ageing effects in the active sensor.

The potential divider circuit is only appropriate interfacing to sensors, which exhibit large changes in resistance, such as metal-oxide sensors. For sensors that do not exhibit large resistance changes – such as conducting polymer sensors – an interface circuit that can facilitate a much higher sensitivity is required. One such circuit is the Wheatstone bridge.

The Wheatstone bridge
In the measurement of small resistance changes, the Wheatstone bridge is an attractive alternative to the potential divider. By employing this topology, the output signal will be due to chemisorption alone, because the signal component due to baseline resistance is subtracted, and so the bridge output signal can be subjected to a high gain stage. The bridge methodology has been employed in the past by Cole et al. (1999); Gardner et al. (1998) and Shurmer et al. (1993) as a front-end conditioning circuit for conducting-polymer chemoresistors. Figure 9 shows the Wheatstone bridge configuration.

The output voltage of the bridge circuit is given by the following equation:

\[
V_{OUT} = V_{IN} \left( \frac{R_S}{R_S + R_1} - \frac{R_3}{R_2 + R_3} \right)
\]  

(17)

It can be seen by comparing equation (17) with equation (1), that the output voltage from the bridge follows the output of the potential divider circuit, but with an offset voltage subtracted. The plot of Figure 10
displays the output characteristic for the widely used form of the bridge, \( R_1 = R_2 = R_3 = R \), where \( R \) is the sensor baseline resistance – see equation (3). From the plot, it is evident that the removal of the voltage component due to the baseline resistance facilitates amplification of the output signal; thus, very high overall sensitivities are achievable.

The sensitivity of the Wheatstone bridge is given by:

\[
S = \frac{\partial V_{\text{OUT}}}{\partial V_{\text{IN}}} = \frac{V_{\text{IN}} R_1}{(R_S + R_1)^2} \tag{18}
\]

It can be seen from equation (18) that the Wheatstone bridge has the same sensitivity as the potential divider. However, as stated earlier, because the baseline-offset component is removed, the output signal can be subjected to a high amplification stage. Thus, a very high overall sensitivity is achievable.

Consequently the sensitivity equation now becomes:

\[
S = A V_{\text{IN}} \left( \frac{R_1}{R_S + R_1} \right) \tag{19}
\]

where \( A \) is the amplifier gain.

As can be seen from equation (19), the sensitivity is proportional to both the input voltage \( V_{\text{IN}} \) and the amplifier gain \( A \).

Test case analysis for Wheatstone bridge

In the Wheatstone bridge circuit of Figure 9, the voltage across the sensor \( V_S \) is given by the expression:

\[
V_S = V_{\text{IN}} \frac{R_1}{R_1 + R_S} \tag{20}
\]

From equations (20) and (6) we obtain an expression for the excitation voltage in terms of the power dissipated in the sensor:

\[
V_{\text{IN}} = \left( 1 + \frac{R_1}{R_S} \right) \sqrt{P_S R_S} \tag{21}
\]

From the previously defined test case parameters, the maximum input voltage \( V_{\text{IN}}^{\text{MAX}} \) is:

\[
V_{\text{IN}}^{\text{MAX}} = 6.32 \, \text{V} \tag{22}
\]

Substituting into equation (19) and assuming an amplifier gain of 20 \( (A = 20) \), a value for the maximum sensitivity is obtained:

\[
S_{\text{MAX}} = 3.16 \, \text{mV/}\Omega \tag{23}
\]

Comments on the Wheatstone bridge

Normally the bridge is operated in balanced mode (i.e. null mode), but it may also be operated in unbalanced mode (i.e. deflection mode) (Doebelin, 1990). It can be balanced manually, but for sensor array applications it is more likely to be balanced automatically – perhaps as part of a smart sensor system. A high degree of temperature compensation can be achieved via the use of a passivated sensor in a bridge arm adjacent to the active sensor.

The Wheatstone bridge configuration is the signal conditioning methodology used by many commercial gas sensors today (Gardner et al., 2002). However, the common bridge topology as shown in Figure 9, suffers from the following drawbacks: first, any interconnect or lead-wire resistance between the reference resistor and the sensor can result in errors (Hatfield et al., 1994), making the

Front-end signal conditioning

Khalil Arshak, Gerard Lyons, Leon Cavanagh and Seamus Clifford

Figure 9 The Wheatstone bridge arrangement

Figure 10 A plot of the un-amplified and amplified output voltage \( (A = 6) \) of the Wheatstone bridge circuit as a function of \( \beta \) \( (V_{\text{IN}} = 10 \, \text{V}) \)
system unsuitable for remote sensor interrogation, and secondly, its output displays a non-linear characteristic with large resistance swings. However, various techniques have been developed to counteract this non-linearity (Pearce et al., 2003b).

**Constant-current resistance interrogation circuit**

The Wheatstone bridge demonstrates how a very high overall sensitivity can be achieved (via amplification) when the relatively large baseline component of the voltage across the sensor is removed, and so the output voltage is due to chemisorption alone. The following technique is based on the constant-current potential divider, but it also employs the benefit of offsetting the baseline voltage signal. In sensor array applications, this offset voltage is usually provided via a DAC, as there is need to provide various values of offset signal for the different sensors of the array. Neaves and Hatfield (1995) have used this circuit arrangement for the interrogation of conducting-polymers as part of an electronic nose system. The circuit is shown in Figure 11.

With the constant current potential divider, this technique forces a constant current through the sensor. This results in a voltage across the sensor that is proportional to the sensor resistance (Neaves and Hatfield, 1995). The baseline voltage signal is then offset in a unity gain differential stage. The sensitivity can now be greatly increased via the use of a high gain voltage amplifier (gain = $A$).

The output voltage for the system is given by the following equation:

$$V_{OUT} = A(I_S R_S - V_{OFF})$$

where $A$ is the amplifier gain.

As can be seen from the graph of Figure 12, the circuit possesses an inherently linear transfer function.

The sensitivity of the system is given by the expression:

$$S = \frac{\partial V_{OUT}}{\partial R_S} = AI_S$$

As can be seen from equation (25), the sensitivity is proportional to both the current through the sensor ($I_S$) and the gain of the amplifier ($A$).

**Test case analysis for the constant-current resistance interrogation circuit**

From equation (14), we have previously calculated the maximum current allowable through the sensor to be:

$$I_{S\text{MAX}} = \text{0.316 mA}$$

Substituting into equation (25) and assuming an amplifier gain of 20 ($A = 20$) a value for the maximum sensitivity is obtained:

$$S_{\text{MAX}} = 6.32 \text{ mV/}\Omega$$

**Comments on the constant-current resistance interrogation circuit**

Advantages of this circuit include: its linear output signal with changing sensor resistance and the ability to achieve a high overall sensitivity – due to the baseline component being removed from the output signal.

A disadvantage of the circuit is the effect of temperature on the output voltage; however, the software may subsequently compensate for these unwanted effects.
The ratiometric op-amp circuit

In arrays of odour sensing chemoresistors, baseline resistances can vary greatly. For example, polymer-based resistive sensors can be fabricated with baseline resistance values in the range of tens of ohms to mega ohms (Harris et al., 1997). Also, these chemoresistors have a large temperature co-efficient of resistance ($\sim 10^{-2/\circ C}$) (Cole et al., 2001). A signal conditioning circuit that address both these problems is based on a ratiometric measurement principle, which removes common-mode effects (Gardner et al., 2002). This methodology has been implemented in the past by Dyer and Gardner (1997) and Chueh and Hatfield (2002) as an interface circuit to conducting-polymer sensors. The principle is implemented via the use of two identical chemoresistors (where $R_i$ is passivated with an impermeable coating) in an op-amp circuit (Cole et al., 2001) (Figure 13).

The circuit might be classed as an advanced form of the active divider. The virtual earth created by the first op-amp configuration sees a current, which is modulated by the passivated chemoresistor ($R_i$), injected into the sensor. The baseline voltage output signal from the first op-amp is then offset in a unity gain differential stage. The sensitivity of the system can now be greatly enhanced via the use of a high gain voltage amplifier. The output voltage for the system is given by the following equation:

$$V_{OUT} = A \left(-V_{IN} \frac{R_S}{R_i} - V_{OFF}\right) \quad (28)$$

Figure 14 shows the output signal characteristic. Since the output voltage is linear with the changing sensor resistance and as discussed earlier this linearity can facilitate subsequent processing stages.

![Figure 13: The ratiometric op-amp circuit](image)

The sensitivity of the system is given by:

$$S = \frac{\partial V_{OUT}}{\partial R_S} = -A \left(\frac{V_{IN}}{R_i}\right) \quad (29)$$

From equation (29) it can be seen that increasing either the input voltage ($V_{IN}$) or the amplifier gain ($A$) increases the magnitude of the sensitivity of the system.

Test case analysis for ratiometric op-amp circuit

Using equation (14) the maximum allowable current through the sensor has previously been calculated as:

$$I_{S_{MAX}} = 0.316 \text{ mA} \quad (30)$$

Assuming that $R_i$ is a perfect (passivated) copy of $R_S$ then due to the virtual earth:

$$V_{IN_{MAX}} = I_{S_{MAX}} R = 3.16 \text{ V} \quad (31)$$

For an excitation voltage of $-3.16 \text{ V}$ ($V_{IN} = -3.16 \text{ V}$) and an amplifier gain of 20 ($A = 20$), the maximum sensitivity is calculated from equation (29) as:

$$S_{MAX} = 6.32 \text{ mV/} \Omega \quad (32)$$

Comments on the ratiometric op-amp circuit

Advantages of the circuit include: a linear output signal with changing sensor resistance (Figure 16), the baseline voltage component is removed from the output signal allowing a high overall sensitivity to be achieved through amplification, the output voltage’s reduced sensitivity to temperature and sensor drift effects due to the input current being “regulated” by the passivated chemoresistor and the output voltage will be independent of wide variations in baseline resistance of the sensors if $R_i$ and $R_S$ are sufficiently matched (Cole et al., 2001; Gardner et al., 2002).

Constant-voltage resistance interrogation circuit

In the constant-current resistance interrogation circuit, a constant current was forced through the sensor and the resultant...
voltage across the sensor was the variable being monitored. An alternative to this technique is to maintain a constant voltage across the sensor, with the current through the sensor becoming the monitored variable.

Neaves and Hatfield (1995) have employed this methodology in the interrogation of arrays of conducting polymer sensors.

Figure 15 shows the implementation of this method.

As discussed earlier, in signal conditioning circuits the signal component due to the baseline resistance is offset; in this circuit it is offset using a current source. The sensitivity of the circuit is then enhanced via the use of a current amplifier. The output current of the system is given by the following equation:

\[ I_{\text{OUT}} = A \left( I_{\text{OFF}} - \frac{V_S}{R_S} \right) \] (33)

The sensitivity of the system is proportional to both the gain of the current amplifier and the source voltage, as can be seen from the following equation:

\[ S = \frac{\partial I_{\text{OUT}}}{\partial R_S} = A \left( \frac{I_S}{R_s} \right) \] (34)

It can be seen from equation (34) that the sensitivity of the circuit is proportional to both the current through the sensor and the amplifier gain.

**Test case analysis for constant-voltage resistance interrogation circuit**

Using equation (14), the maximum allowable current through the sensor has previously been calculated as:

\[ I_{S_{\text{MAX}}} = 0.316 \text{ mA} \] (35)

Hence, the maximum excitation voltage \( V_{S_{\text{MAX}}} \) is:

\[ V_{S_{\text{MAX}}} = I_{S_{\text{MAX}}} R \]

\[ = 0.316 \times 10^{-3} \times 10 \times 10^3 \]

\[ = 3.16 \text{ V} \] (36)

For an excitation voltage of 3.16 V \( (V_S = 3.16 \text{ mA}) \) and an amplifier gain of 20 \( (A = 20) \), the maximum sensitivity is calculated from equation (34) as:

\[ S_{\text{MAX}} = 0.632 \mu\text{A/}\Omega \] (37)
Comments on the constant-voltage resistance interrogation circuit

An advantage of this circuit is the use of current as the measurand variable, as it can allow greater flexibility and simplicity in subsequent analogue signal processing circuitry (Neaves and Hatfield, 1995). Disadvantages of this circuit include its non-linear output characteristic (see Figure 16) and the effects of sensor temperature on the current output signal. However, as stated earlier, these effects can be compensated for in the software.

Discussion

Table I summarises the characteristic equations and test case results for each of the front-end signal conditioning circuits investigated.

From the analysis and derived sensitivity equations it is clear that amplification is a very important factor in achieving high overall circuit sensitivity. As can be seen from the test case results, the circuits with the poorest sensitivities are the constant-voltage potential divider and the constant-current potential divider. Although the sensitivities of these circuits may be increased with amplification, the improvement would only be marginal due to the presence of the baseline voltage component in the amplified signal. It can be seen from the test case results that in terms of sensitivity, the better performing circuits all realise the benefit of removing the sensor baseline voltage. The Wheatstone bridge employs the simplest method of offsetting the baseline voltage, via the use of a second potential divider. However, as the same voltage source provides both the sensor excitation voltage and the offset voltage it can be seen from Table I that the bridge has half the inherent gain of circuits 4 and 5, which use separate voltage sources to offset the baseline voltage component.

As discussed earlier, a signal conditioning circuit with a linear output characteristic lends itself to the task of odour analysis and classification. For this reason, it would appear that of the circuits analysed, the best performance, in terms of sensitivity and linearity are the constant-current resistance interrogation circuit and the ratiometric op-amp circuit. The ratiometric op-amp circuit has the further advantage of eliminating the effect of temperature from the baseline output signal via the use of a passivated copy of the active sensor; hence it may be concluded that, of the front-end signal conditioning circuits analysed, the ratiometric op-amp circuit addresses most of the previously defined issues. For this reason, it is the most appropriate circuit for interfacing to thin-film conducting polymer sensors.

Conclusions

A review has been carried out of front-end signal conditioning circuits, which have been employed as part of the electronic nose systems. The relevant equations regarding the operation and characteristics of these circuits have been derived. Advantages and disadvantages of each methodology with respect to interfacing to odour sensitive chemoresistors have been presented and discussed. All of the investigated circuits have been subjected to a specific test case to quantitatively compare the performance of each front-end circuit with respect to

Table I Summary of the characteristic equations and test case results for the signal conditioning circuits analysed

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Output signal equation</th>
<th>Linear output characteristic</th>
<th>Sensitivity equation</th>
<th>Maximum sensitivity (test case results)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant-voltage potential divider</td>
<td>$V_{OUT} = \frac{V_s R_S}{R + R_S}$</td>
<td>No</td>
<td>$S = \frac{V_s R_S}{(R + R_S) R}$</td>
<td>0.158 mV/Ω</td>
</tr>
<tr>
<td>Constant-current potential divider</td>
<td>$V_{OUT} = I_n R_S$</td>
<td>Yes</td>
<td>$S = I_n$</td>
<td>0.316 mV/Ω</td>
</tr>
<tr>
<td>Wheatstone bridge</td>
<td>$V_{OUT} = AV_{IN} \left( \frac{R}{R + R_S} - \frac{R}{R + R_F} \right)$</td>
<td>No</td>
<td>$S = A \left( \frac{V_s R_S}{(R + R_S) R} \right)$</td>
<td>3.16 mV/Ω</td>
</tr>
<tr>
<td>Constant-current resistance interrogation circuit</td>
<td>$V_{OUT} = A(I_n R_S - V_{OFF})$</td>
<td>Yes</td>
<td>$S = A I_n$</td>
<td>6.32 mV/Ω</td>
</tr>
<tr>
<td>Ratiometric op-amp circuit</td>
<td>$V_{OUT} = A \left( -V_{IN} \frac{R_S}{R} - V_{OFF} \right)$</td>
<td>Yes</td>
<td>$S = -A \left( \frac{V_s R_S}{(R + R_S) R} \right)$</td>
<td>6.32 mV/Ω</td>
</tr>
<tr>
<td>Constant-voltage resistance interrogation circuit</td>
<td>$I_{OUT} = A \left( I_{OFF} - \frac{V_s R_S}{R} \right)$</td>
<td>No</td>
<td>$S = A \left( \frac{V_s R_S}{(R + R_S) R} \right)$</td>
<td>0.632 mA/Ω</td>
</tr>
</tbody>
</table>
interfacing a thin-film conducting-polymer sensor. Of the circuits reviewed, it has been concluded that the ratiometric op-amp circuit is the most suitable to use as an interface to conducting-polymer sensors.

References

Gardner, J.W., Vidi, M., Ingelby, P., Pike, A.C., Brignell, J.E., Scivier, P., Bartlett, P.N., Duke, A.J. and