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Electronic nose system design and analysis

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Abstract. This paper presents the design and analysis of a conditioning circuit for Metal-Oxide Semiconductor (MOS) gas sensors within an electronic nose system. By effectively addressing the challenges of signal amplification, filtering, and stabilization, the proposed circuit enhances the reliability and accuracy of gas detection. The system architecture, which includes temperature control and signal modulation, is optimized for precise Odor identification in various applications, ranging from industrial safety to healthcare diagnostics. Simulation results demonstrate the circuit's ability to improve sensor performance, ensuring accurate and reproducible measurements.

1 Introduction

Electronic noses represent a key innovation in the detection of gases and volatile compounds, offering a qualitative, cost-effective, real-time, and portable method to reliably and reproducibly measure a wide range of Odors[1]. Electronic noses are inspired by the complexity of biological olfactory systems and are designed to replicate the functionalities of the human nose while overcoming some of its limitations, such as variability due to human factors like mood, hormonal cycles, or desensitization through habituation[2].
The importance of electronic noses lies in their ability to perform repetitive detection tasks without fatigue while maintaining consistent performance even in challenging conditions. For example, in industrial environments, where chemical Odors and effluents can be unpleasant or potentially hazardous, electronic noses provide an accurate and reliable solution, avoiding the biases and limitations associated with human smell[3].
The applications of electronic noses are vast and constantly expanding. They are already used in the food and beverage industry to control product quality, as well as in the pharmaceutical industry to monitor manufacturing processes[4-8]. In health care, electronic noses are being explored for their potential to diagnose diseases through the analysis of patients' breath. This non-invasive approach could revolutionize medical diagnostics by offering a quick and practical method to identify conditions such as diabetes, lung infections, or even certain types of cancers[9]. Additionally, electronic noses are finding promising applications in security and personal identification[10].
Despite their growing relevance across industries, the full potential of electronic noses hinges on the performance of their core components: the sensors. At the heart of the electronic nose are MOS (Metal-Oxide Semiconductor) gas sensors, widely used for their sensitivity and ability to detect a broad range of volatile compounds. However, effectively utilizing MOS sensors presents several challenges[11]. While the sensors are crucial for detecting a variety of gases, the technical difficulties associated with their use must be addressed to ensure optimal performance. MOS sensors often produce weak and noisy electrical signals, necessitating proper conditioning to achieve reliable results. Signal conditioning involves crucial steps such as voltage regulation, amplification, filtering, and signal stabilization. A well-designed conditioning circuit is therefore essential to maximize the accuracy and reliability of measurements while minimizing interference and unwanted fluctuations[12,13].
However, despite these advances, challenges remain in improving sensor performance and optimizing signal processing, which are critical for ensuring reliability and accuracy. This paper focuses on addressing these challenges by proposing a novel electronic conditioning circuit that enhances the stability and quality of signals from Metal-Oxide Semiconductor (MOS) sensors, a key component of electronic noses.

2 Electronic nose implementation

2.1 System Overview

The electronic nose system presented in this paper is designed to capture, condition, and analyze signals from MOS gas sensors, enabling precise identification of odor samples. As illustrated in Fig.1, the system architecture integrates several key components, including a sensor chamber, a conditioning circuit, and a data acquisition module. With this optimized configuration, the system provides an efficient solution for detecting and identifying gaseous compounds present in various samples[14].

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The process begins with the extraction of the Odor sample from a sampling container, where a gaseous sample is introduced using a pump. Fresh air is also injected into the sensor chamber to provide a baseline reference and improve measurement accuracy. An electronic valve device controls the admission of gases into the sensor chamber, which houses several MOS gas sensors. These sensors react to the different chemical components present in the Odor sample, generating electrical signals proportional to the concentration of the detected gases[15].

These raw electrical signals, emitted by the sensors, are then transmitted to the conditioning circuit, which plays a crucial role in the initial data processing. This circuit is responsible for amplifying, filtering, and stabilizing the signals from the sensors, making them suitable for further analysis. Voltage regulation and noise reduction within this circuit ensure that the conditioned signals are accurate and reliable[16].

The conditioning circuit plays a critical role in enhancing the performance of Metal-Oxide Semiconductor (MOS) gas sensors in an electronic nose system. This circuit is designed to improve the quality of the raw signals received from the sensors by addressing common issues such as signal noise, instability, and low signal strength. Key components of the conditioning circuit include amplifiers, filters, and voltage regulators, which work together to ensure that the sensor output is accurately processed before further analysis. Signal amplification is necessary to boost the weak electrical signals generated by MOS sensors when exposed to gases, while filtering eliminates high-frequency noise and unwanted interference. Additionally, voltage regulation ensures a stable power supply, which is essential for maintaining consistent sensor performance. A well-designed conditioning circuit can significantly enhance the accuracy and reliability of gas detection by minimizing the influence of external factors such as temperature fluctuations and environmental noise[13].

The conditioned signals are then sent to a data acquisition board, which converts the analogy signals into digital data. These data are subsequently stored on a computer using Signal Express software. The analysis of the stored data is performed by applying pattern recognition algorithms, which allow the identification of characteristic Odor profiles of the analysed samples. The results of this analysis determine the chemical composition of the Odor samples and enable precise identification. The proposed system thus combines multiple technologies to form a comprehensive and effective solution for Odor detection and analysis, illustrating the potential of electronic noses in various applications.

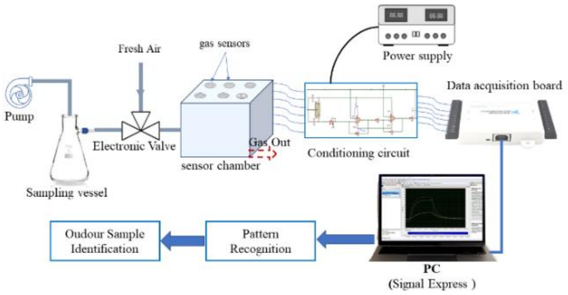

Fig. 1. The diagram of the E-Nose system shows the Odor detection process.

2.2 Metal-oxide sensors

Metal oxide sensors are widely used for gas detection due to their simplicity, low cost, and high sensitivity. Their high sensitivity is due to the direct interaction between gas molecules and the metal oxide surface at the nanoscale as shown in Fig.2. The large surface area of the metal oxide grains amplifies these interactions, leading to significant changes in electrical properties even at low gas concentrations. The operating principle is based on variation in the electrical conductivity of the metal oxide when exposed to gases. These variations are caused by chemical interactions between gas molecules and the oxide surface, thereby altering the concentration of charge carriers and, consequently, the sensor's resistance. The operating temperature is a crucial element in the performance of metal oxide sensors. Typically, these sensors require high temperatures, often between (100 - 400°C)[12], to maximize their sensitivity. At these temperatures, chemical reactions on the sensor's surface are intensified, enhancing gas detection. High temperatures accelerate the adsorption and desorption processes of gases on the sensitive surface, which is essential for the sensor's responsiveness and accuracy. Resistance parameters, such as Rh (heated sensor resistance) and Rs (gas-sensitive resistance), are essential for understanding the sensor's response. By measuring these resistances, it is possible to determine the concentration of the detected gas and ensure accurate measurements while considering environmental conditions like humidity and ambient temperature. The sensitivity of metal oxide sensors is defined by their ability to detect low concentrations of gases and produce a proportional electrical response. This sensitivity depends on several factors, such as the type of oxide used, grain size, specific surface area, and operating conditions like temperature[12]. Sensitivity can be improved by modifying the material's morphology and adding specific catalysts. Finally, the detection limits refer to the minimum gas concentration that the sensor can reliably detect. Achieving low detection limits is crucial for critical applications, such as air quality monitoring or detecting hazardous gas leaks. Optimizing the sensitive materials and operating conditions enhances these limits, making metal oxide sensors suitable for a broad range of industrial and environmental applications.

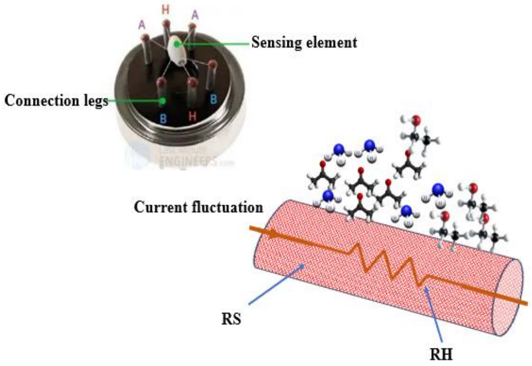

Fig. 2. Metal-oxide sensors

2.3 Sensor's electronic circuit

The circuits presented in Fig.3 and Fig.4 is essential for signal conditioning in the Electronic Nose (E-Nose) system, processing the electrical signals generated by the sensor's sensitive resistance (Rs) and regulating the temperature of the heating element (Rh). These two elements are crucial for ensuring the reliability and accuracy of gas measurements. The system is composed of two main sub-circuits: one for measuring Rs and the other for controlling Rh. Together, these sub-circuits ensure that the sensor signals are properly amplified, filtered, and stabilized before being sent to the analysis system. By enabling precise conversion of Rs variations into electrical signals and maintaining a stable temperature via Rh, this circuit ensures reliable and reproducible gas measurements. The stability and precision provided are fundamental to the overall performance of the E-Nose system, particularly for the accurate detection and identification of chemical compounds present in the air, representing a key step in the development of sophisticated and efficient gas detection systems.

2.4 Temperature Control

Metal oxide gas sensors are often used in isothermal mode, where the sensor's temperature remains stable during exposure to Odors. The most common and simplest method to achieve pseudo-isothermal operation is to apply a current or voltage to the resistive heater RH, as illustrated in Fig. 3.

Fig.3 illustrates a control circuit designed to manage the heating power in an MQ-type gas sensor system. This circuit incorporates several essential components that work together to ensure precise temperature regulation of the sensor's detection element. Below is a detailed description of the components and their roles in this circuit:

The PN2907A [17] is a PNP transistor that acts as a switch in this circuit. It controls the current passing through the heating resistors RH1, RH2, and RH3. This transistor is controlled by the TL084 operational amplifier, which regulates the current according to the required temperature for the gas sensor. The PN2907A is essential for adjusting the heating power and, consequently, the temperature of the sensor's sensitive element.

The TL084 [18] operational amplifier is configured as a voltage comparator. It compares a reference voltage, usually derived from a voltage divider (not shown here), with a voltage from the circuit. The LM741 then regulates the current through the PN2907A transistor to stabilize the temperature of the heating resistors (RH1, RH2, and RH3). This process is crucial for maintaining the gas sensor at the optimal temperature, ensuring accurate gas detection.

RH1, RH2, RH3: These resistors, each with a value of 10 ohms, constitute the heating element of the gas sensor. They are responsible for heating the detection element to a specific temperature, which is essential for the sensor to function properly. A precise temperature is necessary for the MQ sensor to reliably detect and measure gases.

The R5 resistor, with a value of 33 ohms, plays a protective role in the circuit. It limits the current passing through the TL084 operational amplifier, thus protecting it from potential overcurrent's that could occur in the circuit. Additionally, it helps stabilize the circuit's operation by ensuring that the current remains within a safe range.

The LM317T [19] is an adjustable voltage regulator used to provide a precise and regulated output voltage to the various components of the circuit. It allows the output voltage to be set at a desired level by adjusting the values of the resistors in the voltage divider. The precision of the LM317T is crucial to ensuring that the circuit operates correctly, without unwanted voltage fluctuations. R4 and R3: These resistors form a voltage divider that determines the output voltage of the LM317T regulator. The R4 resistor is 720 Ω, and the R3 resistor is 240 Ω. Depending on these values, the output voltage of the LM317T is adjusted to meet the circuit's needs. This voltage divider is critical for setting the voltage that will power downstream elements of the circuit, such as the gas sensor.

The capacitors C1 and C2 are used to filter out fluctuations and interference in the power supply. They stabilize the regulated voltage produced by the LM317T, eliminating noise and sudden voltage variations. This guarantees that the circuit receives a clean and stable power supply, which is essential for the reliable operation of the gas sensor.

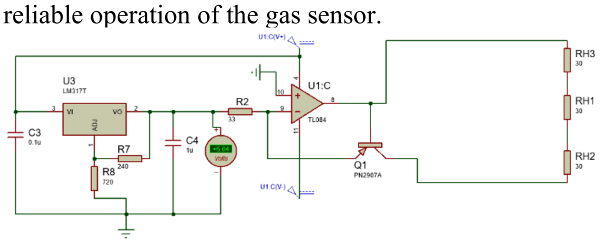

Fig. 3. Electronic Conditioning Circuit for Heater Control

The output voltage of the LM317 circuit is provided by:

$$V_{out} = V_{ref}\left(1 + \frac{R7}{R8}\right) + I_{Adj}R8 \qquad (1)$$

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2.5 Conditioning circuit

Fig.4 illustrates a conditioning circuit for an MQ-type gas sensor, where the sensor's sensitive resistance, Rs, is integrated into an amplification and filtering circuit. This circuit is designed to convert variations in Rs into a measurable voltage that can be used for gas detection applications.

Filtering Unit: The low-pass filter, composed of resistor RF and capacitor CF, is designed to attenuate high-frequency noise components from the sensor's output signal. This filter ensures that only the relevant signal passes through, while reducing any unwanted noise. The cutoff frequency fc of this filter is determined by the following equation:

$$f_c = \frac{1}{2\pi R_F C_F} \quad (2)$$

Where RF and CF determine how much noise is filtered out.

Amplification Unit: An amplification or gain stage is usually necessary to boost the signal from the interface circuits to a level that fits within the appropriate dynamic range. of an analogy-to-digital converter (ADC). The gain is set by resistors R1 and R3.

The gain of this stage is given by :

$$V_{U1:B} = -\frac{R1}{R3} V_{U1:A} \quad (3)$$

This means that increasing R1 or decreasing R3 will result in a stronger signal. The amplification ensures that the small variations in the sensor's output can be accurately detected and processed by the system.

Measurement Unit: A constant voltage measurement circuit uses a ground connection at the inverting input of the operational amplifier is used to maintain a constant voltage Vin across the sensor RS. The negative feedback through a load resistor results in an output that varies linearly with the conductance of the sensor.

$$V_{U1:A} = -\frac{RL}{Rs} V_{IN} \quad (4)$$

This equation shows that the output voltage is inversely proportional to the sensor's resistance RS , meaning that as the gas concentration increases (and RS decreases), the output voltage increases, providing a measurable indication of gas presence.

Power Supply: The 7805-voltage regulator provides a stable 5V supply to the circuit. Capacitors C1 and C2 are used to filter power supply fluctuations, ensuring stable circuit operation[20].

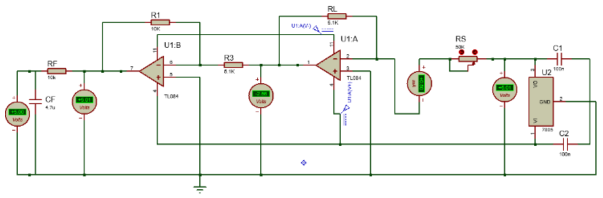

Fig. 4. Electronic Conditioning Circuit for Sensing Resistance

2.6 Modulation circuit

In our E-Nose system, precise control of the sensor's temperature is crucial to ensuring reliable and reproducible gas detection while improving the system's sensitivity, selectivity, and repeatability (R). Fig.5 illustrates an astable multivibrator circuit used for modulating the temperature of the MQ sensor's heating element (Rh).

The NE555 timer, used as a square wave generator in a stable mode, is the core of this circuit. Resistors R1 and R2, in conjunction with capacitor C1, determine the frequency and duty cycle of the oscillation, thus defining the period of the square wave produced at the output (pin 3)[21]. Capacitor C2 stabilizes the circuit by reducing interference, ensuring stable and reliable operation. The output V_{out} powers the sensor's heating element. By controlling the frequency and duty cycle of the square wave, it is possible to modulate the power supplied to the heating element, and consequently, its temperature. This modulation is essential for adjusting the sensor's temperature according to the specific gas detection requirements, thereby optimizing the MOS sensor's sensitivity and selectivity[22].

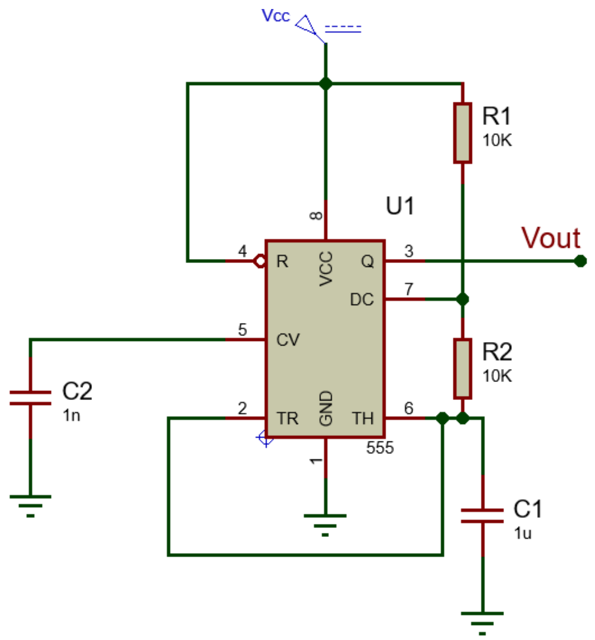

Fig. 5. Generator Circuit, Pulse Width Modulation

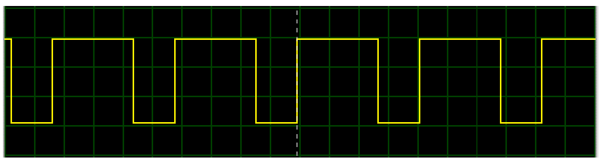

Fig. 6. Voltage applied to the heating resistance

Fig.6 shows the square wave output generated by the NE555 in a stable mode. This output is used to modulate the temperature of the MQ sensor's heating element. The periodic signal allows for cyclical control of the heating, thereby optimizing gas detection by adjusting the sensor's temperature.

3 CONCLUSIONS

The overall efficiency of an electronic nose system is determined by the performance of its individual components. While often overlooked, it is clear that careful design and selection of the upstream signal conditioning circuit are essential for achieving excellent performance in Odor detection systems. Indeed, the system's accuracy and reliability largely depend on the quality of the processing of the electrical signals generated by the gas sensors. By ensuring proper amplification, filtering, and stabilization, this circuit plays a critical role in the efficiency of detecting and analysing the chemical compounds present in the air. Therefore, paying close attention to the design of this circuit significantly contributes to improving the electronic nose's overall sensitivity and precision, thereby enhancing its practicality in real-world applications. In the future, we plan to use this system for real-time fish quality evaluation, which highlights its potential in food safety and quality monitoring.

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