High-accurate Resistance Measurement Method for Sensor Circuit

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Abstract. An accurate resistance measuring circuit which is used complementary measurement and input compensation to make radiometric method as ideal as possible and reduce the influence that OAs’ stray terms results based on radiometric method and dual-slope ADC circuit is proposed to solve the problem that we can’t balance the precision and detection range of resistance measurement. The accuracy of method is almost related to the reference resistor. It can be calculated that the resistances near the reference resistance measurement error is less than 0.02% after using the complementary measurement under the high-precision OAs, and the measurement error is an order of magnitude smaller after using the input compensation. It is shows that the measurement error could be less than 1% with non-precision OAs. This circuit can be widely applied to sensor circuit.

Key words: accurate resistance measurement, auto compensation, radiometric method, dual-slope ADC.

1. Introduction
Accurate measurement of resistance is an important part of industrial control and precision instruments[1, 2]. The accuracy of the resistance determines the accuracy of the entire system or device. In particular, the nanowire NO₂ gas sensor has a small change in resistance at a low concentration of NO₂, and whether this change value is accurately measured directly affects the accuracy of the sensor. The traditional resistance measurement methods are proportional method and voltage current method[3]; for the μΩ class resistance, there are DC constant current source method, low frequency alternating current measurement method and large pulse current measurement method; For the MΩ class resistance, use large voltage measurement method and electrometer method and so on. Among these methods, the small resistance measurement method increases the power consumption of the circuit greatly, and is not suitable for the measurement of the sensor resistance of about 100 Ω. The electrometer method has certain limitations on the measurement of the resistance of the sensor, the proportional method and the voltage-current method are affected by the offset of the lower-stage amplifier, which in turn affects the resistance measurement. Therefore, the NO₂ sensor resistance is usually measured by a voltage divider or a bridge connected to a reference resistor, and then the characteristic curve of the sensor is used to estimate the gas concentration value. However, the bridge method greatly reduces the measurement
accuracy when the resistance changes slightly, which limits the range of measurement. Therefore, it is difficult to achieve measurement accuracy and range using electronic circuits, especially in the case where the change in sensor resistance is nonlinear with the gas concentration. This paper proposes a measurement method based on the ratio-based and dual-slope ADC circuit structure, which ensures the measurement range and measurement accuracy, and is more suitable for the resistance measurement of NO₂ sensors. This circuit has advantages of good proportionality, low temperature dependence, and the use of spurious terms to compensate for errors automatically. The circuit uses a calibrated reference resistor to minimize global error, so the error can only be considered to depend on the stability and tolerance of the nanowire resistor, and the associated error with the peripheral circuit interface is negligible[4].

2. Principle of precision resistance measurement

2.1. Precision Resistance Measurement Circuit Structure

Since the frequency of the NO₂ sensor resistance change is very low and the high measurement accuracy and range is required, the circuit structure of the dual-slope A/D converter is very satisfactory. Based on the dual-slope A/D converter, this paper designs a circuit suitable for measuring nanowires. The simplified diagram is shown in Fig.1. The PWM signal is generated in the closed loop, and its signal average is equal to the Vₛ. The voltage divider consists of a reference resistor RREF and a nanowire resistor RNW.

By applying levels Vₚ and Vₜ to the voltage divider and using the same voltage level for the same PWM, the duty cycle DPWM₁ of the PWM signal is equal to the ratio D of the voltage divider voltage. The PWM signal is converted by exchanging Vₚ and Vₜ. This measurement is a complementary measurement. In this case, D is equal to the PWM duty cycle DPWM₂, DPWM₂ refers to the PWM off state. As shown in Fig.2.

Nanowire resistance can be calculated by equation (1) or equation (2):

\[ D = \frac{R_{NW}}{R_{NW} + R_{REF}} \]  

(1)

\[ D_{PWM,1} = D_{PWM,2} = D \]  

(2)
\( R_{nw} = R_{ref} \cdot D_{PWM, 1} / (1 - D_{PWM, 1}) \) \hspace{1cm} (3)

\( R_{nw} = R_{ref} \cdot D_{PWM, 2} / (1 - D_{PWM, 2}) \) \hspace{1cm} (4)

\( D_{PWM, 1} \) and \( D_{PWM, 2} \) are calculated through the duration of the PWM-ON and PWM-OFF states using the digital logic, which are measured using an up counter with a clock frequency of \( f_{clk} \).

The frequency of the PWM changes with the change of \( D \). As shown in the equation (3), when the value of \( D \) is 50% (\( R_{nw} = R_{ref} \)), the \( f_{PWM} \) obtains the maximum value \( f_{PWM, MAX} \).

\( f_{PWM} = 4f_{PWM, MAX} \cdot D(1 - D) \) \hspace{1cm} (5)

2.2. **Theoretical Resolution**

Theoretically, the resolution depends on the change of the minimum countable duty ratio \( \Delta D_{min} \), as shown in equation (6).

\( \Delta D_{min} = f_{PWM} / f_{clk} \) \hspace{1cm} (6)

The measurement resolution can be calculated by combining equations (1) and (5) with equation (6), and the result is as shown in equation (7).

\( \Delta R_{ref \cdot min} / R_{nw} = 4f_{PWM, MAX} / f_{clk} \) \hspace{1cm} (7)

This constant can be determined in the design. Using a clock with frequency of around tens of MHz, the resolution can be easily less than 0.1%.

2.3. **Analog Error Compensation Caused by Integrator Input Stray Term**

As shown in Fig.3, in the measurement of the voltage division ratio \( D \), due to the spurious term at the input pin of the integrator, the duty cycle of the actual PWM is different from \( D \), as shown in equations (8) and (9).

![Figure 3. Analogue integrator stray terms](image)

\( D_{PWM, 1} = D \cdot \left[ 1 + \frac{R_{ref} \cdot i_p}{(V_p - V_n)} + \frac{(V_{ref} - R \cdot i_p)}{(V_p - V_n)} \right] + \frac{(V_{ref} - R \cdot i_p)}{(V_p - V_n)} \) \hspace{1cm} (8)

\( D_{PWM, 2} = D \cdot \left[ 1 - \frac{R_{ref} \cdot i_p}{(V_p - V_n)} - \frac{(V_{ref} - R \cdot i_p)}{(V_p - V_n)} \right] - \frac{(V_{ref} - R \cdot i_p)}{(V_p - V_n)} \) \hspace{1cm} (9)

From the formula, the error caused by the spurious term for calculating \( D_{PWM, 1} \) and \( D_{PWM, 2} \) is only the difference in sign, so the error can be compensated by the average duty cycle measurement, as shown in equation (10).
\[ D_{AVG} = \frac{D_{PWM,1} + D_{PWM,2}}{2} \approx D \] (10)

3. Construction and correction of accurate resistance measurement circuit

3.1. Construction of Accurate Resistance Measurement Circuit

The resistor readout circuit shown in Fig. 4. It consists of three main parts:

Reference Level Generator: \( V_P \) and \( V_N \) are generated by a simple voltage divider. Since this method is scale based, the value of the voltage divider may not be accurate.

Dual-slope A/D converter[5]: The output of the integrator is squared by a comparator, and its output is connected to a digital logic circuit to drive the level-shift switch \( SW_{PWM} \). In order to avoid the error caused by the propagation delay of \( SW_{PWM} \), even the duty cycle \( (D_{PWM}) \) of PWM can not be measured from it, so the driving signal of \( SW_{PWM} \) needs to use a fast CMOS.

Commutator switch: The switches \( SW_{PWM}, SW_{ref} \) and \( SW_{nw} \) repeatedly switch the levels \( V_P \) and \( V_N \) to measure the resistance through the circuit. \( SW_{ref} \) and \( SW_{nw} \) are composed of an operational amplifier, in order to prevent impedance mismatch, which will lead to the voltage output deviation.

![Accurate resistance measurement circuit](image)

**Figure 4.** Accurate resistance measurement circuit

3.2. Accurate Resistance Measurement Circuit Error Analysis

The effectiveness of analog error compensation depends on the sensitivity of the operational amplifier's stray term to the input common-mode voltage, which means that the stray term cannot be considered as a constant. Therefore, the duty cycle \( D \) calculated according to the results in equation (10) is still inaccurate. The difference consists of equations (11) and (12) [6].

\[ \delta D = D - D_{AVG} = \delta D_1 + \delta D_2 + \delta D_3 \] (11)

\[ \delta D_1 = \frac{1}{(A_0 + 1)} (D - 1/2) \]

\[ \delta D_2 = -\frac{A_0}{(A_0 + 1)} \cdot \frac{1}{2(V_P - V_N)} \left[ D \cdot \Delta V_{ofs}^{ref} - (1 - D) \cdot \Delta V_{ofs}^{nw} \right] \] (12)

\[ \delta D_3 = \frac{1}{2(V_P - V_N)} (\Delta V_{ofs}^{int} + D \cdot R_{ofs} \cdot \Delta i_{ofs}^{int} - R \Delta i_{ofs}^{int}) \]

Where \( \Delta V_{ofs}^{int}, \Delta V_{ofs}^{ref}, \) and \( \Delta V_{ofs}^{nw} \) are the offsets of the op amp input, which are the changes from the normal measurement period to the complementary measurement period. Similar \( \Delta i_{ofs}^{int} \) and \( \Delta i_{ofs}^{int} \) are the changes in the op amp bias current of the integrator, and \( A_0 \) is the dc gain of the op amp.

The remaining term \( \delta D \) introduces the influence of the non-ideality of the device on the resistance measurement. The error analysis is shown in the figure. The error region is calculated using a precision.
and high precision CMOS operational amplifier, and assumes that the input common mode is in a solid linear relationship with the stray terms. The assumptions are as follows:

\[ V_{CC} = 5V; \quad V_{P} = 3V; \quad V_{N} = 2V; \quad A_0 \geq 10^5; \quad R_{ref} = 2.7k\Omega; \quad R \leq 10k\Omega \]

Maximum input offset and bias current offset: \( (\Delta V_{CM} \leq 1V) \)

Precision CMOS Operational Amplifier: \( (\Delta V_{\text{int ofs}}, \Delta V_{\text{ref ofs}}, \Delta V_{\text{nw ofs}}) \leq 100\mu V; \Delta V_{P}, \Delta V_{N} \leq 10nA \)

High precision CMOS operational Amplifier: \( (\Delta V_{\text{int ofs}}, \Delta V_{\text{ref ofs}}, \Delta V_{\text{nw ofs}}) \leq 10\mu V; \Delta V_{P}, \Delta V_{N} \leq 1nA \)

The curve about D and measurement error is plotted by calculation. As shown in Fig.5, the error of the precision COMS operational amplifier is between the two blue curves, and the measurement error of D around 50% is about 0.02%; The error of the high precision COMS operational amplifier is between the two red curves, and the measurement error of D around 50% is about 0.005%.

**Figure 5. Theoretical Measurement Error**

### 3.3. Integrator Input Correction

The remaining term \( \delta D \) can be greatly reduced by fixing the common mode input voltage of the integrator to the midpoint of the supply voltage \( V_{CC} \), as shown in Fig.6. Through closed-loop regulation, the input common-mode of the integrator is detected through the non-inverting op amp pin and is regulated by a subsequent proportional-integral circuit, which increases or decreases the \( V_{P} \) and \( V_{N} \) common mode voltages and moves and maintains to the \( V_{CC} \) midpoint. Since the integrator input common mode voltage is always \( V_{CC}/2 \), the stray term can be effectively compensated, and the \( \delta D_3 \) term in the remaining term \( \delta D \) is completely eliminated.

**Figure 6. VP and VN shift for input integrator maintence at fixed value**

The above method can also effectively eliminate \( \delta D_2 \) in the remaining term \( \delta D \), because the input common mode change of \( OA_{ref} \) and \( OA_{nw} \) is related to \( D \) as described in equation (13). According to equations (12) and (14), it can be found that \( \Delta V_{\text{ref ofs}} \) is negligible when \( D \approx 1 \), and the weight of \( \Delta V_{\text{nw ofs}} \) in \( \delta D_2 \) is the smallest. When \( D \approx 0 \), the weight of \( \Delta V_{\text{ref ofs}} \) in \( \delta D_2 \) is the smallest, and \( \Delta V_{\text{nw ofs}} \) is negligible.
\[
\Delta V_{ref} = 2 \cdot (V_p - V_n) \cdot (1 - D)
\]
\[
\Delta V_{acc} = -2 \cdot (V_p - V_n) \cdot D
\]
\[
\Delta V_{ref}^{ref} \approx \alpha_{ref} \cdot \Delta V_{ref} = 2 \alpha_{ref} \cdot (V_p - V_n) \cdot (1 - D)
\]
\[
\Delta V_{me}^{ref} \approx \alpha_{me} \cdot \Delta V_{me} = -2 \alpha_{me} \cdot (V_p - V_n) \cdot D
\]

This method makes the remaining term \( \delta D \) almost only related to \( \delta D_1 \), and \( \delta D_1 \) is related to the DC gain of the operational amplifier. The gain affects the complexity and cost of the ASIC design. The larger the gain, the more complicated the design and the higher the design cost. The correction of the input of the device ensures high-precision measurement using a low-precision operational amplifier. The measurement error using this method is greatly reduced, as shown in Fig. 7, when using a precision op amp, the overall error is an order of magnitude smaller than before the improvement.

![Figure 7. Theoretical measurement error after improvement](image)

4. Simulation of resistance measurement circuit

This paper uses the Simulink tool in Matlab to simulate the behavioral resistor readout circuit. As shown in Fig.8, the circuit is composed of voltage divider, integrator, counter and digital logic. The counter is a twelve-bits counter consisting of a register, an AND gate, and a NOR gate. Since the op-amp during simulation is ideal, a simple voltage divider circuit can be used. A comparator compares the output of the integrator with the comparison value of \( V_{out} \) and \( V_N \). If \( V_{out} \) is larger than \( V_N \), signal a is 1, otherwise signal a is 0. The other comparator compares the comparison value of the input \( V_{in} \) with \( V_{out} \). If \( V_{out} \) is less than \( V_{in} \), signal b is 1, otherwise signal b is 0. We use a switch to selected the \( V_P \) or \( V_N \). The control signal of the switch come from a state machine, which use the signal a and b to control the clock signal of the Flip-flop. the reset signal CLR of the counter is determined by the signal of a&b. When the signal is at the highest or lowest point of Fig.2, the counter is reseted. After completing a triangular wave, the counter finishes two counts, which means a resistance measurement is completed.

![Figure 8. Structure of accurate resistance measurement circuit](image)
We complete the simulation of the readout circuit. In the first measurement, $V_P=5V$, $V_N=0V$, $R_{ref}=3k\Omega$, $R_{nw}=2k\Omega$, the second measurement for compensation $V_P=0V$, $V_N=5V$, the clock period of counter is 1ms, and the the output of the counter after decoding is as shown in Fig.9. The value of the counter of point a and point c is 666, and the value of point b and point of d is 1000. By calculation, the value of $R_{nw}$ measured by this method is 1.998k$\Omega$, and the relative error is 0.1%.

![Figure 9. Counter’s output with 1ms clock cycle](image)

5. Testing
The circuit is composed of STM32 which controls the switch of $V_P$ and $V_N$, LM358 that is a two channels OA forming the integrator and voltage follower with 50 nA bias current and 2.9 mV offset voltage, LM393 that is a comparator with two channels. STM32 also accomplishes the digital logic with software. LM393 compares the voltage level the input of OA and the output of integrator, it also compares the voltage level the input of OA and $V_P$ (or $V_N$).

The counter is generated from STM32 with 8MHz clock cycle. STM32 received the signals of LM393 and controls the switch according to the signals. Because of the resistance of nanowire NO$_2$ sensor being from hundreds of Ohm to ten thousands Ohm, the test focuses on the resistance smaller than 100k$\Omega$. The value of reference resistance is 9.871k$\Omega$.

In Fig.10 there are reported that the relationship between ratio which equals undertesting resistance divided by reference resistance and measurement error. The measurement error could be easily less than 1%. But its measurement error is larger than the theoretical value because of the precision of LM358 and the offset of LM393.

![Figure 10. Testing result](image)

6. Conclusion
A resistance measurement which is easily implement and high precision is proposed. The circuit makes the ratiometricity method as ideally as possible and becomes easily realizing by using embedded equipment. The results of measurement error is only depended on the precision of reference resistance. According to the demo PCB the measurement error is less than 1% with non-precision OAs. The circuit has been designed for nanowire NO$_2$ sensor and it could widely apply to any kinds of sensors.
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