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LEAD COMPENSATION IN A PWM SENSOR INTERFACE

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Abstract: *Error analysis of a resistive sensor-to-microcontroller interface based on pulse width modulation (PWM) and time ratio measurement (sensor resistance over reference resistor), shows that leads resistance produce zero, gain, and nonlinearity errors. Because at the calibration points these errors are nulled out, several calibration resistors selected according to the sensor resistance range would reduce those errors in the full range. Two-point calibration and time ratio measurement yield errors smaller than 1 Ω for lead resistance of 10.5 Ω and sensor resistance from about 600 Ω to 3550 Ω, which is the typical variation range for a PT1000 temperature sensor.*

Keywords: Sensor interface, Lead resistance compensation

1 INTRODUCTION

Direct sensor-to-microcontroller interfaces without intervening ADC are simple to design and less expensive than interfaces based on the classical sensor-amplifier-ADC approach. Daugherty [1] proposed a PWM technique for A/D conversion using a microcontroller and Cox [2] applied it to resistive sensor interfacing (Figure 1).

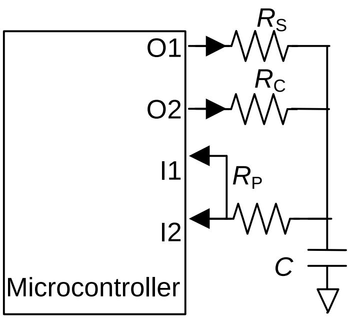


Figure 1. A/D conversion by PWM and time-ratio measurement.

By programming a "high" level (V_{OH}) at output O1, capacitor C charges through the sensor R_S up to a voltage level determined by the logic "1" threshold (V_{IH}) of input I1. Then C is discharged through a protection resistor R_P by setting I2 low ("0", V_{OL}). Port I2 is kept at low level for a time long enough to fully discharge the capacitor. Next, O1 is brought to the tri-state level and O2 is set "high" to charge C through the calibration resistor R_C. The time to charge C is monitored again by checking the level at input I1, and C is discharged anew through R_P. The voltage at I1 changes from V_{IH} to V_{OL} and the pulse width depends on the time needed to charge C (Figure 2).

Since C is the same for both time measurements, taking the ratio cancels its contribution. The result is

$$R_S = \frac{t_S}{t_C} R_C \qquad (1)$$

However, uncertainly in output and threshold voltages involved in the modulation process, internal microcontroller parameters such as output and input resistance and leakage currents, and the resistance of connection leads limit the resolution and accuracy of the process depending on the range for the sensor resistance. This paper analyzes these errors and provides two simple methods to reduce them.

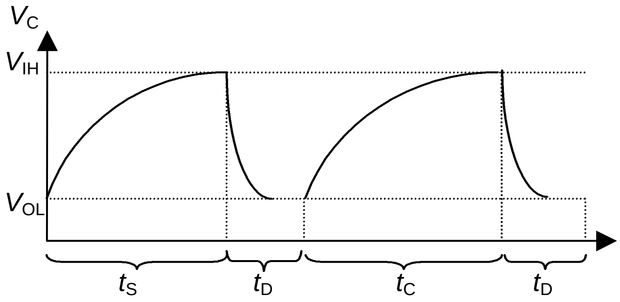


Figure 2. Voltage changes detected at I1. t_S and t_C are the time intervals needed to charge the capacitor C through R_S and R_C respectively. The discharge time t_D through R_P is the same in both cases.

2 MODEL

We use the analysis method described in [3] for this kind of circuits. Figure 3 shows the model for the circuit in Figure 1 when considering lead resistance (R_L) and C charges through a three-wire sensor.

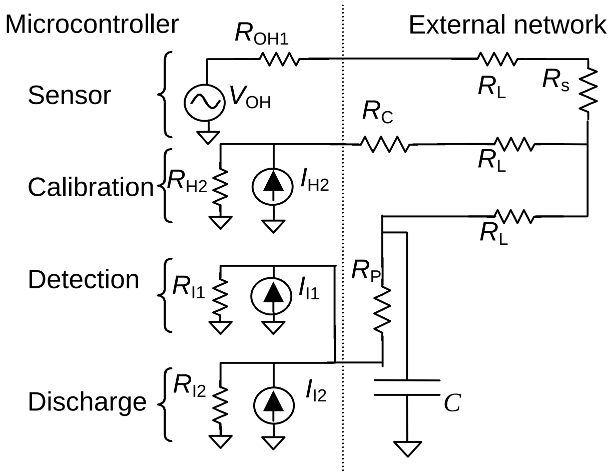


Figure 3. Complete model for the circuit shown in Figure 1 when the capacitor C is charged through the sensor resistance R_S, which is remotely connected using the three-wire technique.

The active output port has finite resistance R_{OH1}. The tri-state output connected to R_C has finite resistance R_{H2} and leakage current I_{H2}. Inputs I1 and I2 are also modeled by a finite resistance (R_{I1} and R_{I2}) and leakage current source (I_{I1} y I_{I2}). The three resistors R_L model lead resistances.

The circuit in Figure 3 can be simplified into the circuit in Figure 4, based in an RC equivalent network that includes an additional current source (I_{EQS}) and a shunt equivalent resistance (R_{EQS}). When C charges through R_C, the model is similar, but because of possible differences between output ports we now have R_{H1} and I_{H1} instead of R_{H2} and I_{H2}, and the equivalent elements when analyzing Figure 3 are R_{EQC} and I_{EQC}.

$$R_{EQS} = (R_{I1} \parallel R_{I2} + R_P) \parallel (R_{H2} + 2R_L) \tag{2}$$

$$I_{EQS} = I_{I1} + I_{I2} + I_{H2} \tag{3}$$

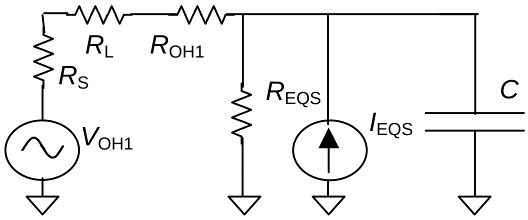


Figure 4. Equivalent circuit of the model in Figure 3.

We can estimate the value for the sensor resistance from equations (1), (2), and (3) by

$$R_S^* = \frac{t_S}{t_C} R_C = \frac{\frac{R_{EQSS}}{R_{EQCC}} \ln\left[\frac{V_{AS} - V_{IH}}{V_{AS} - V_{OL}}\right]}{\ln\left[\frac{V_{AC} - V_{IH}}{V_{AC} - V_{OL}}\right]} R_C = \frac{\frac{(R_{OH1} + R_S + R_L)}{(R_{OH1} + R_S + R_L) + R_{EQS}} \ln\left[\frac{V_{AS} - V_{IH}}{V_{AS} - V_{OL}}\right]}{\frac{(R_{OH2} + R_C + R_L)}{(R_{OH2} + R_C + R_L) + R_{EQC}} \ln\left[\frac{V_{AC} - V_{IH}}{V_{AC} - V_{OL}}\right]} R_C \tag{4}$$

where V_{AS} and V_{AC} are, respectively, the equivalent source voltage when charging through the sensor and through the calibration resistor. When $R_C = R_S$, the terms with logarithms are similar.

Equation (4) shows that there is a zero error, a gain error, and a nonlinearity error. These errors depend on the lead resistances and other parameters. If ports O1 and O2 are identical, these errors are zero for $R_S = R_C$. This suggests to choose $R_C = R_S(0) = R_0$, the mid range value for R_S. Errors for other sensor resistances depend on R_L and microcontroller parameters in Figure 3, which depend on technology but manufacturers do not wholly specify them.

3 EXPERIMENTAL RESULTS AND DISCUSSION

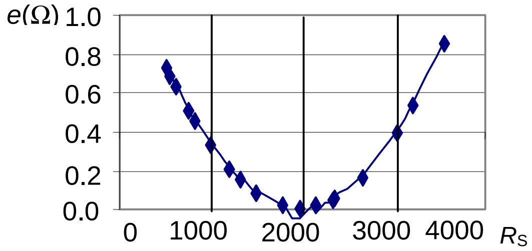
We have built the circuit in Figure 1 using the PIC16C71 microcontroller (Microchip Technologies). Because of the inherent ±1 count uncertainty in time measurements C must be selected large enough for the desired resolution.

Using the design equation stated in [3] and considering a typical variation margin for a resistive temperature sensor Pt1000, that is ΔR_S = 3551.1 Ω – 618.5 Ω = 2936.6 Ω, and n = 10 bits, we need C > 730 nF. We have used 1 µF. We have simulated connecting leads by R_L = 10.5 Ω.

We have also measured the microcontroller parameters not specified in data sheets and determined the coefficients in (4). The best straight-line approach to the resulting equation is

$$R_S^* = 0.9617 R_S + 76.367\,\Omega \tag{5}$$

The nonlinearity error is smaller than 0.5 Ω and it is null at the calibration point (Figure 5).



(a)

Figura 5. Nonlinearity error (equation (4)) when R_C = 2000 Ω, the microcontroller is the PIC16C71, and 618.5 Ω < R_S < 3551.1 Ω.

The best straight-line approach to the experimentally measured resistances is

$$R_S^{**} = 0.96 R_S + 73.54\,\Omega \tag{6}$$

There are zero and gain errors, and they are close to those for R_S^*. Selecting a calibration resistor close to the actual sensor resistance reduces nonlinearity errors (figure 5). Therefore, if ΔR_S is relatively large for the desired resolution, we can define several calibration points and select the most suitable point according to a first guess obtained for a value close to the midrange value for R_S. Alternatively, we can use two calibration points to find the approximated transfer characteristic for a given microcontroller and use it to find the actual R_S from the measured R_S^{**} when in equation (1) we select $R_C = R_S(0)$. Figure 6 shows the absolute error when applying this procedure using calibration resistors equal to the extrema for R_S. The maximal error is 1 Ω.

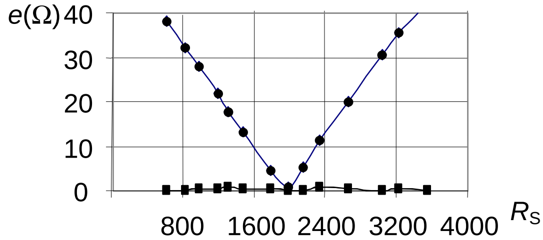


Figure 6. Absolute error when using only equation (1) (circles) and when also using the transfer characteristic estimated from two calibration resistors (squares).

4 CONCLUSION

Sensor-to-microcontroller interfaces based on PWM and time ratio measurement have zero, gain, and nonlinearity errors due to sensor leads, and also due to the finite input and output resistances and leakage currents of digital ports (equation (4)). Ratio measurements reduce errors only for sensor resistances close to the calibration value. Therefore, one method to reduce errors is to perform time ratio measurements using a calibration resistor selected according to the measured sensor resistance. However, this procedure does not use all the information that the several calibration resistors needed provide. An improved method uses two calibration resistors to estimate the actual transfer characteristic and then performs a time ratio measurement using a calibration resistor close to the mid range value for the sensor. This procedure applied to a sensor whose resistance goes from about 600 Ω to 3550 Ω reduces the absolute error to 1 Ω when connecting leads have 10.5 Ω. Because of the thermal coefficient of resistance wires, that calibration should be repeated periodically.

REFERENCES

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