Modeling and Simulation of a Wheatstone Bridge Pressure Sensor in High Temperature with VHDL-AMS

Sahbi Baccar[1], Timothée Levi[1], Dominique Dallet[1], François Barbara[2]

[1]*IMS Laboratory – University of Bordeaux*
351, Cours de la Libération – 33405 Talence Cedex France
{sahbi.baccar, timothee.levi, dominique.dallet}@ims-bordeaux.fr

[2]*Schlumberger Etudes et Productions*
1, Rue Henri Bequerel-92140 Clamart France
barbara@clamart.oilfield.slb.com

Abstract- This paper presents a model of a Wheatstone bridge sensor in VHDL-AMS. This model is useful to take into account the temperature effect on the sensor accuracy. The model is developed on the basis of a resistor model. Simulations are performed for three different combinations of parameters values. They confirm the resistors mismatch effect on the sensor accuracy in high temperature (HT).

Keywords: Wheatstone bridge, sensor, resistance, mismatch, high temperature, VHDL-AMS

I.   Introduction

Using sensors is mandatory in many industrial fields. These systems are essential for the accomplishment of many industrial processes [1]. Their great asset is their capacity to convert physical quantities to electrical signals that can be treated in specific circuits. Sensors have to be robust, accurate and insensitive to external parasites or to the environment conditions. Unfortunately, some sensors are constrained to work in extreme conditions (high pressure, high temperature, etc.) In order to limit the errors caused by the environment, it is necessary to model the dependency of the sensor performance to the environment. This modelling effort starts with a first step of characterization that could lead to mathematical relations linking the performance parameters to the environment ones (temperature, pressure, etc) [1], [2].

In this work, we examine the influence of the temperature on the Wheatstone bridge sensor. Many modeling approaches were used to model the environment effect on this sensor performance: geometrical modelling [2], [3] analytical and physical modeling [4] and behavioural modeling [5], [6], [7], [8]. In our work, we model the effect of the resistors mismatch in HT on its accuracy using VHDL-AMS language. This choice is argued briefly by reminding VHDL-AMS advantages comparing to other languages. Section II describes the Wheatstone bridge sensor structure. It gives the relation showing the dependency between the input voltage and the output voltage. Section III details the development of the model and the simulation results

II.   Wheatstone bridge

Fig. 1 describes a well-known structure of a "Wheatstone bridge" sensor formed with four resistances and used to measure the pressure. This is possible as the resistance value depends on the pressure. In this circuit, three resistances are supposed to be ideally similar and have known values ($R_1=R_2=R_3=R$). The value of the fourth resistance R_s is unknown. It can be calculated by using Kirchoff Laws as shown in the equation (1).
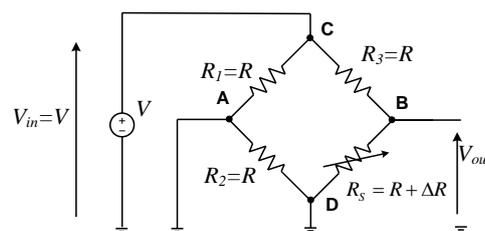

Figure 1: Wheatstone bridge sensor structure

$$V_{out} = V_B - V_A \approx V \frac{\Delta R}{4R} \qquad (1)$$

The relation between V_{out} and V_{in} is linear and depends obviously on R_S but also on the nominal resistance R. V_{out} is not measured directly; it will be rather filtered and amplified as a signal by further appropriate instrumentation circuits.

III. Development of a VHDL-AMS model of a Wheatstone bridge in HT

As explained in [9], [10], [11], modelling of industrial electronics in HT requires development of accurate models. In [4], we confirmed that the SPICE model of an industrial op-amp is inaccurate in [120°C, 220°C]. In [9], we compared many modelling approaches and languages to model performances of different circuits of an analog front-end (AFE). In [4], it was shown that VHDL-AMS can offer excellent capacities to meet the real challenges that are behind modeling of conventional electronics and overcome the limitations problem of SPICE. The detailed development is well described in [10]. It is based on a measurement campaign of the performance parameters of the considered circuit. Two examples of circuits were already modeled with the selected modeling language VHDL-AMS: an ADC and an op-amp. We continue to use the same modelling language in this work.

The resistor is the elementary component of the Wheatstone bridge. It will be more practical to develop first a resistor model in VHDL-AMS (Fig.2.a). The Wheatstone bridge model will be created by instantiating this resistor model in the sensor model (Fig.2.b). The dependency of the resistor to the temperature is described by equation (2), where T is the considered temperature and T_0 is the reference temperature. $R(T)$ and $R(T_0)$ are respectively the resistances values in T and T_0. TC_1 and TC_2 are called temperature coefficients.

$$R(T) = R(T_0) + R(T_0)\left[TC_1(T - T_0) + TC_2(T - T_0)^2 \right] \qquad (2)$$

We denote xi, {i=1, 2, 3, s} the resistances variations after temperature increasing. The x_i factors depend on the temperature coefficients $TC1R_i$ and $TC2R_i$, {i=1, 2, 3, s}. Expressions of xi factors are more detailed in equations (3)-(6). The resistor model and the Wheatstone bridge-model are illustrated by Fig.2. The advantage of reusing the models and instantiating them are clearly illustrated in Fig. 2. b.

```
LIBRARY IEEE;
USE IEEE.ELECTRICAL_SYSTES.ALL;
---------Declaration de l'entité resistor_temp--------

ENTITY resistor_temp IS
  GENERIC (R    : REAL := 1.0e3;
           TC1   : REAL := 0.0;
           TC2   : REAL := 0.0;
           temp: REAL );

  PORT (TERMINAL p,m: electrical
        );
END ENTITY resistor_temp;
------------------------------------------------------
ARCHITECTURE behav_temp_resistor OF resistor_temp IS
CONSTANT temp0 : REAL := 27.0;
QUANTTY V ACROSS I THROUGH p TO m;
QUANTITY Rt: REAL;
BEGIN
Rt == Rt*(1.0+TC1*(tep-temp0)+TC2*(temp-temp0)**2);
V  == I*Rt;
END ARCHITECTURE behav_temp_resistor;
```
(a)
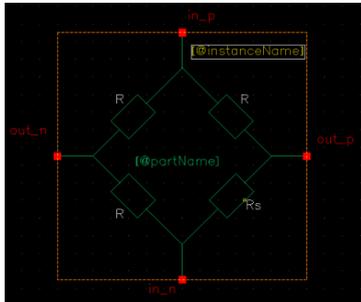
(c)

```
LIBRARY IEEE;
USE IEEE.ELECTRICAL_SYSTES.ALL;
---------Declaration de l'entité Pont_wheatstone_temp---
ENTITY Pont_wheatstone_temp IS
GENERIC (temp : REAL;
         R    : REAL;
         TC1_R1: REAL;
         TC2_R1: REAL;
         TC1_R2: REAL;
         TC2_R2: REAL;
         TC1_R3: REAL;
         TC2_R3: REAL;
         delta_Rs : REAL;
         TC1_Rs: REAL;
         TC2_Rs: REAL
);
------Architecture de l'entite Pont_wheatstone_temp--------
ARCHITECTURE behav_temp OF Pont_wheatstone_temp IS

CONSTANT Rs: REAL := R + delta_Rs;

BEGIN

R1: ENTITY resistor_temp(behav_temp_resistor)
       GENERIC MAP(R,TC1_R1,TC2_R1,temp)
       PORT_MAP(in_p,out_n);

R2: ENTITY resistor_temp(behav_temp_resistor)
       GENERIC MAP(R,TC1_R2,TC2_R2,temp)
       PORT_MAP(out_n,in_n);

R3: ENTITY resistor_temp(behav_temp_resistor)
       GENERIC MAP(R,TC1_R3,TC2_R3,temp)
       PORT MAP(in_p,out_p);

Res_s: ENTITY resistor_temp(behav_temp_resistor)
       GENERIC MAP(Rs, TC1_Rs, TC2_Rs,temp)
       PORT MAP(out_p,in_n);

END ARCHITECTURE;
```
(b)

Figure 2: (a) : HT resistor model , (b) : HT Wheatstone bridge model,
(c) : Generated Wheatstone Bridge Model

$$R_s(T) = R(T_0) + \Delta R(T_0) + \Delta R_s(T, T_0) = R_0 + + \Delta R + x_s \quad (3)$$

$$R_1(T) = R(T_0) + \Delta R_1(T, T_0) = R_0 + x_1 \quad (4)$$

$$R_2(T) = R(T_0) + \Delta R_2(T, T_0) = R_0 + x_2 \quad (5)$$

$$R_3(T) = R(T_0) + \Delta R_3(T, T_0) = R_0 + x_3 \quad (6)$$

The theoretical effect of the resistance mismatch in HT is described by equation (7).

$$V_{out}(T) = \frac{V}{2}\left[\frac{\Delta R + x_s - x_3}{2R + x_s + x_3} - \frac{x_2 - x_1}{2R + x_1 + x_2} \right] = \frac{V}{2}.\alpha(T, \Delta R, R) \quad (7)$$

According to (7), the relation between V_{out} and V_{in} is always linear. However, the slope α of the linear curve depends on the resistance variation x_i, the temperature T and on the nominal resistance R. If all x_i are equal, we can prove that V_{out} is unchanged even if the temperature T increases. This means that in order to guarantee a precise measurement in HT, resistances have to be almost similar (they have almost the same variation x_i).

$$V_{out}(T) = \frac{V}{2}.\frac{\Delta R}{2R + 2x} \approx \frac{V\Delta R}{4R} \approx V_{out}(T_0) \quad (8)$$

The simulation results are illustrated by Figure 3 and table 1. We have considered 3 cases of simulations. Each case represents specific values combination of T, $TC1R_i$, and $TC2R_i$ (R=1KΩ, ΔR=1Ω). The table 1 compares the theoretical values and the simulation values of V_{out} when V_{in}=1V. It is clear that that there is a good agreement between VHDL-AMS simulation result and theoretical value of V_{out}. This good agreement validates the VHDL-AMS Wheatstone bridge model in HT.

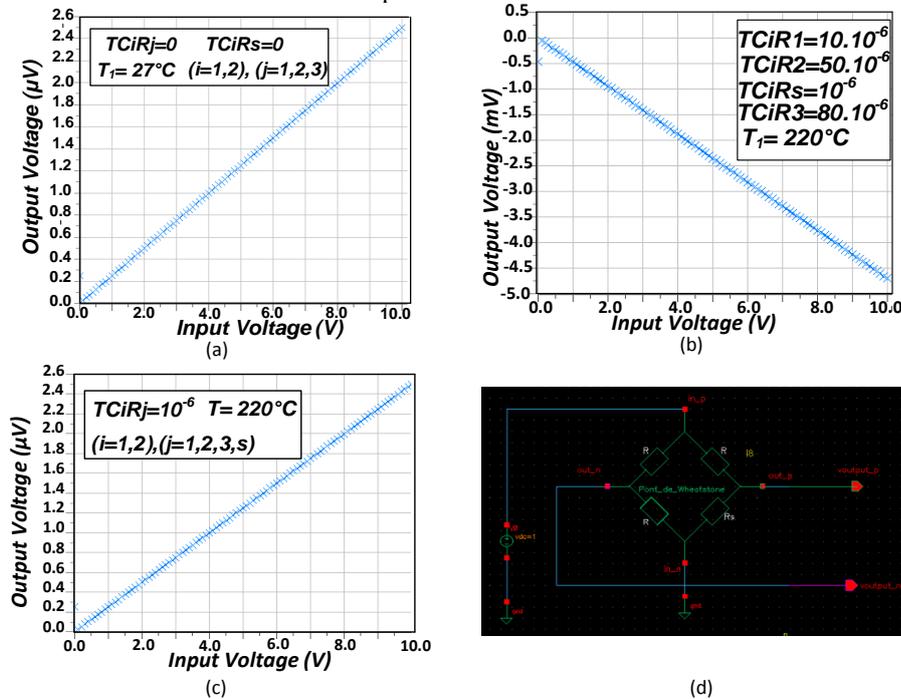|	$T=27°C$, $TC1R_i = TC2R_i = 0$	$T=220°C$, $TC1R_i = TC2R_i = 10^{-6}$	$T=220°C$, $TC1R_i \neq TC1R_j$, $TC2R_i \neq TC2R_j$
$V_{out,th}$ (theoretical value)	250μV	250μV	-467,2mV
$V_{out,sim}$ (simulation)	249,86 μV	249,863μV	-470,05mV

Table1: Comparison of simulation results

Figure 2: Evolution of V_{out} as function of V_{in} for different parameters combination of T, $TC1R_i$ and $TC2R_i$ (a, b and c), (d): generated symbol in the test test-bench

With a DC analysis of the test-bench which is represented in Figure 3.d, we plotted V_{out} as function of V_{in} .As predicted, the evolution of V_{out} as function of V_{in} is always linear. Moreover, if all resistances variations x_i are equal (second case in the tab. 1), the slope of the linear curve does not change in 220°C. But, if the temperature coefficients are not identical (third case in tab. 1), the slope value and sign change in 220°C. That is why; for a same input voltage V_{in} =1V, V_{out} has a different value in each case (V_{out}= 249,863μV in the second case and -470,05mV in the third case). This means that due to the changing of the temperature coefficients values, V_{out} does not only changes its sign, but its absolute value increase also considerably as it is almost multiplied by about 2000 times. This can cause serious errors to the instrumentation amplifier which is close to the Wheatstone bridge.

II. Conclusions

This paper is a continuty of previous works that aim to model AFE circuits in HT [9], [10], [11]. We developed a VHDL-AMS model of a Wheatstone bridge sensor. Formed by four resistances, this sensor is very sensitive to temperature variation. First, we created a VHDL-AMS model of a resistor for wich the temperature effect is described by two temperature coefficients. Then, by using the instantiating property, the HT VHDL-AMS model of the Wheatstone bridge model is created. This model was first validated by comparing simulation results to the theretical results. Then, an example of the effect of resistance mismatch due to the temperature increasing was simulated in 220°C. This confirms the impact of the temperature on this sensor accuracy.

In future works, it will be interesting to study the effect of the Wheatotine bridge sensor error in the instrumentation and measurement analog foront-end circuits. We can especially study the effect of these errors on the instrumentation amplifier which is the first circuit after the sensor. The already developed model of the AFE circuits can ensure such simulation and can enable even a suitable dimensionning of their performance dependly on the desired application.

References

[1] H. S. Kalsi, "Electronic Instrumentation", McGraw Hill, 2010
[2] K. H. Diener, S. Reitz, G. Brokmann, P. Schneider, H. Übensee, H. Bartuch, "Modeling and Simulation of Integrated Piezo-resistive Pressure Sensors", 22nd CAD-FEM Users' Meeting 2004, International Congress on FEM Technology, Dresden, Germany
[3] A. Talić, S. Ćerimović, F. Kohl, , R. Beigelbeck, F. Keplinger, and J. Schalko, "FEM Analysis of Micromachined Flow Sensor with Wheatstone Bridge Read-out", the Proceedings of the COMSOL Conference 2008 Hannover
[4] S. Cerimovic1, R. Beigelbeck2, H. Antlinger3, J. Schalko2, B. Jakoby3, and F. Keplinger1 "Combined Analytical and Numerical Modeling of a Resonant MEMS Sensor for Viscosity and Mass Density Measurements", the Proceedings of the COMSOL Conference 2011,Tokyo
[5] E. Martín, L. Barrachina, C. Ferrer, "Practical Case Example of Inertial Mems Modeling with VHDL-AMS", Advances in Design and Specification Languages for SoCs, Selected Contributions from Forum on Specification & Design Languages FDL, 2004, Springer 2005
[6] C. Cane, J. Chiao, F.V. Verdu, "Smart sensors modeling using VHDL-AMS for micro instruments implementation with a distributed architecture", Proc. of SPIE Smart Sensors, Actuators, and MEMS II, Sevilla, May 2005
[7] J. Haase, J. Bastian, and S. Reitz "VHDL-AMS in MEMS Design Flow" Forum on Specification & Design Languages FDL '02, Marseille, September 24-27, 2002
[8] E. Martín, C. Ferrer "Design Methodology using VHDL-AMS applied to Inertial MEMS", Eurosensors XVIII, the 18th European Conference on Solid State Transducers, Rome, Italy, 12 - 15 September 2004
[9] S. Baccar, T. Levi, D. Dallet, V. Shitkov, F. Barbara, "Modeling Methodology for Analog Front-End Circuits Dedicated to High-Temperature Instrumentation and Measurement Applications", IEEE Trans. on Inst. and Meas. Vol. 60, no. 5, May 2011
[10] S. Baccar, T. Levi, D. Dallet, V. Shitkov, F. Barbara, "A validity Study of an Industrial SPICE-based Op-amp Macromodel for High Temperature Simulation", IEEE I2MTC Conference, May 2012, Graz, Austria
[11] S. Baccar, T. Levi, S. M. Qaisar, D. Dallet, F. Barbara, "A Behavioral and Temperature Measurements-Based of an Operational Amplifier Using VHDL-AMS", ICECS 2010, December 2010, Athens, Greece