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SENSORS CHARACTERIZATION AND CONTROL OF MEASUREMENT SYSTEMS BASED ON THERMORESISTIVE SENSORS KEPT AT CONSTANT TEMPERATURE

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Abstract – This paper proposes the use of feedback linearization for the characterization of thermoresistive sensors and for the control of measurement systems based on thermoresistive sensors kept at constant temperature. Two important benefits brought by feedback linearization are: regarding sensor characterization, it allows the determination of static and dynamic parameters by a single experimental test; concerning temperature control of the measurement system, it makes the controller design simpler and prevents linear controllers from losing performance due to changes in the operation point. A simple *PI* controller in combination with feedback linearization is then applied to the system. Experimental results for sensor characterization and temperature control are presented.

Keywords: measurement systems, thermoresistive sensors, feedback linearization, sensors characterization.

1. INTRODUCTION

The purpose of this paper is to present the application of feedback linearization technique to measurement systems based on thermoresistive sensors kept at constant temperature.

The characteristic of heat transfer and variation in electric resistance of a device as a function of temperature is explored by measurement systems that use thermoresistive sensor. This type of sensor is commonly used to measure fluid speed, thermal radiation and temperature [1] [2] [3].

The static and dynamic behaviours of the sensor can be represented by a mathematical model obtained from its characterization. The application of feedback linearization to this measurement system makes possible to characterize the static and dynamic behaviours of the sensor in a single test [4]. The works concerning thermoresistive sensors characterization developed so far use distinct experimental tests to determine the static and dynamic behaviours [3] [5] [6].

The measuring methods that use warm sensor are based on constant voltage, constant current or constant temperature [7]. All these methods need to keep constant one variable at least. In the method of constant temperature, the sensor is warmed by Joule effect until it reaches a reference temperature [8].

Hence, to keep constant the sensor temperature, it is necessary to compensate the thermal variation by adjusting the electrical signal applied to the sensor. Thus, a control system can be used to reach this goal, where the control signal is proportional to the measuring.

A linear controller can be more easily designed and implemented than a nonlinear one. However, since the system under analysis is nonlinear, the performance of a linear controller is reduced if the excitation signal is far from the operational point considered in the controller design.

With feedback linearization, a feedback loop is used to linearize the relationship between a new control input and the system output [9]. This way, it is possible to design a linear controller that can be applied over all the operation range of the sensor, resulting thus in a better performance.

A simple PI controller, resulting from an Internal Model Control (IMC) design, is then used to control the sensor temperature.

2. THE THERMORESISTIVE SENSOR

The thermoresistive sensor used in this research is a *NTC* (Negative Coefficient Temperature). To describe the behaviour of a thermoresistive sensor, the equation of energies balance can be used (1), and the equation associating electrical resistance (R_s) and temperature (T_s) can be used as well (2).

$$\alpha SH + P_s(t) = G_{th}[T_s(t) - T_a(t)] + C_{th}\frac{dT_s(t)}{dt} \quad (1)$$

$$R_s(t) = A\exp(B/T_s(t)) \quad (2)$$

where:

α is the sensor transmissivity-absorptivity coefficient,

S is the sensor surface area,

H is the incident radiation,

$P_s(t)$ is the electric power,

G_{th} is the thermal conductance between sensor and ambient,

$T_a(t)$ is the ambient temperature,

C_{th} is the sensor thermal capacity,

$A=R_0exp(-B/T_0)$ (R_0 and T_0 are the resistance and temperature of the sensor at 0^oC, respectively), and B is the temperature coefficient that depends on the sensor composition.

In experimental implementations is common to use voltage or electric current as excitation signal of the system (it is not possible to use electric power directly). Using electric current:

$$P_s(t) = R_s(T_s(t))I_s^{\,2}(t) \qquad (3)$$

Considering constant the ambient temperature T_a, (1) is rewritten as:

$$\alpha SH + R_s(T_s(t))I_s^{\,2}(t) = G_{th}T_\Delta(t) + C_{th}\frac{dT_\Delta(t)}{dt} \qquad (4)$$

where $T_\Delta(t)=T_s(t)-T_a$. Hence, input $I_s(t)$ and output $T_\Delta(t)$ are related by a nonlinear differential equation.

An experimental setup was developed for tests, characterization and control of the sensor temperature (Fig. 1).

The block *ambient with sensor* refers to a close housing where the sensor is kept. Hence, the incident radiation on the sensor surface is null ($H=0$). The internal temperature is monitored by a thermometer in this close housing.

It can be attributed to the *signal conditioning circuit* (Fig. 2):

- (i) Provides the electrical decoupling between the data acquisition system and the sensor;
- (ii) Adjusts the *DAC* sensor excitation signal, and
- (iii) Adjusts the sensor output signal to the *ADC* input requirements.

In this paper, the thermoresistive sensor circuit is highlighted to simplify the theoretical analysis (Fig. 3).

The *data acquisition circuit board* is the *PCI6024E*, produced by National Instruments, and the man-machine interface is developed on *LABVIEW*. A virtual instrument was designed with this software, where a set of control functions allows quickly change the main program, insuring high flexibility on computer programming.

The manufacturer furnishes a table relating electrical resistance and temperature for the *NTC* used. This way, the values of the parameters A and B could be calculated from (2): $A=1354.06e\text{-}5\Omega$; $B=3342.21K$. These parameters characterize the static behaviour of the sensor. The feedback linearization developed in the present work makes possible to determine the dynamic parameter (time constant, τ) and another static parameter (DC gain, G_{th}) in a single test.

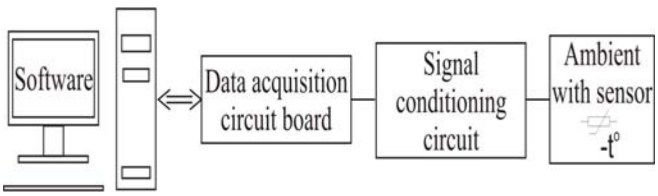

Fig. 1. Block diagram of experimental setup.

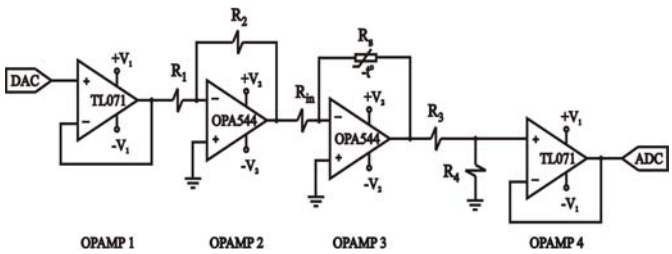

Fig. 2. Developed electronic circuit schematics

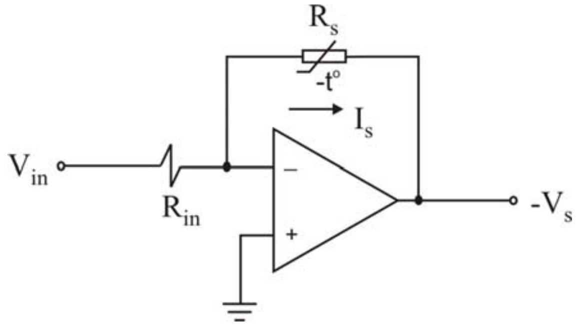

Fig. 3. Electronic sub-circuit.

3. FEEDBACK LINEARIZATION

3.1. Theoretical development

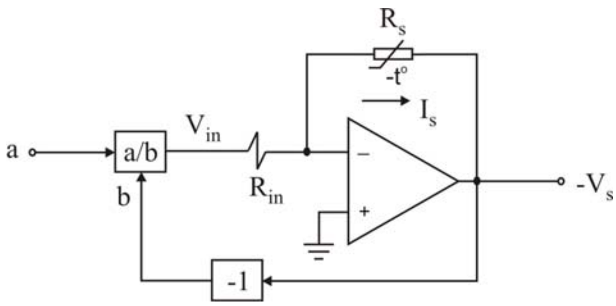

Fig. 4. Electronic sub-circuit with feedback linearization.

The proposed feedback linearization scheme is shown in Fig. 4. From this figure one can deduce:

$$I_s(t) = \frac{V_{in}(t)}{R_{in}} \qquad (5)$$

$$V_{in}(t) = \frac{a(t)}{b(t)} = \frac{a(t)}{V_s(t)} \qquad (6)$$

From (5) and (6),

$$P_s(t) = V_s(t)I_s(t) = \frac{a(t)}{R_{in}} \qquad (7)$$

In this case, $a(t)$ is a virtual variable that is equivalent to the electric power dissipated by the sensor multiplied by the value of R_{in}. It is necessary to define a new input variable

($P_x(t)$) to distinguish this virtual product from the real electric power:

$$P_x(t) = \frac{a(t)}{R_{in}} \tag{8}$$

Considering null the incident radiation ($H=0$), assuming constant the ambient temperature, and adopting the new input variable defined in (8), (1) can be rewritten as:

$$P_x(t) = G_{th} T_\Delta(t) + C_{th} \frac{dT_\Delta(t)}{dt} \tag{9}$$

From this equation one can note that the feedback system is linear with respect to the new input variable $P_x(t)$.

The transfer function in the linearized system (applying the Laplace Transform in (9)) is a first order function:

$$\frac{T_\Delta(s)}{P_x(s)} = \frac{1/G_{th}}{\frac{C_{th}}{G_{th}} s + 1} \tag{10}$$

3.2. Experimental results

The sensor response (10) to a constant power P_{cte} is given by:

$$T_\Delta(t) = \frac{P_{cte}}{G_{th}} (1 - e^{-t/\tau}) \tag{11}$$

where $\tau = C_{th}/G_{th}$.

An increasing stair signal with *100s* per step (to guarantee that the sensor would be operating in steady state) was applied to both systems: without feedback linearization (non-linearized system), and with feedback linearization (linearized system). The responses are shown in Fig. 5 and Fig. 6.

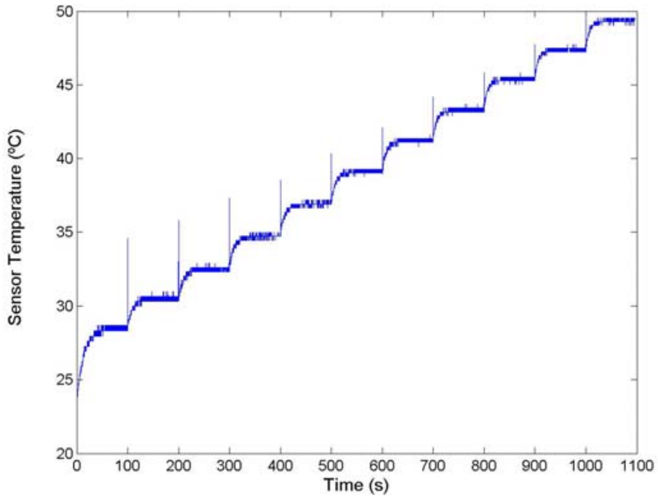

Fig. 5. Output temperature with input in increasing steps (non-linearized system).

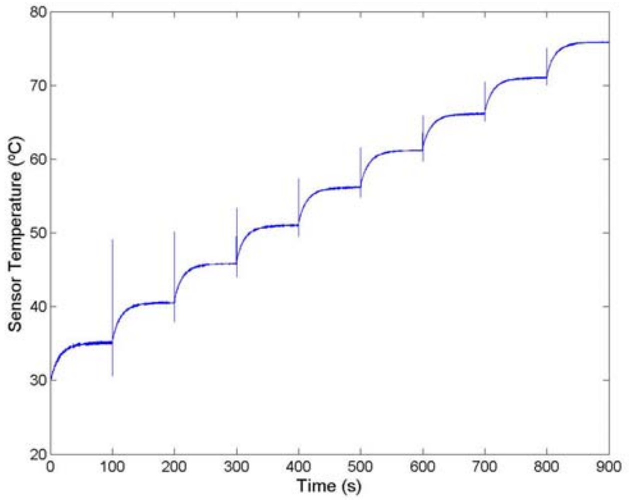

Fig. 6. Output temperature with input in increasing steps (linearized system).

The relation T_Δ/P_{cte} changes when the systems works at different operation points in the non-linearized systems. This time constant is called apparent (τ_a), and it does not correspond to the intrinsic time constant of the sensor (τ). The *DC* gain (G_{th}) is given by:

$$G_{th} = \frac{\overline{P_x}}{\overline{T_\Delta}} \tag{12}$$

where $\overline{P_x}$ and $\overline{T_\Delta}$ are the electrical power and the temperature difference in steady state, respectively.

The results for the static parameter (G_{th}) and dynamic parameter (τ) for both systems are presented in Table 1.

In conclusion, for linearized systems it is possible to determine the static and dynamic behaviours with a single set of experimental data.

Table 1. DC gain and time constant in non-linearized and linearized systems.

Step	Non-linearized		Linearized	
	G_{th} (mW/ºC)	τ_a (s)	G_{th} (mW/ºC)	τ (s)
1	0.80	14.3	1.56	12.0
2	0.80	12.4	1.40	11.3
3	0.82	11.1	1.30	11.3
4	0.80	10.6	1.29	11.3
5	0.81	10.1	1.26	11.6
6	0.82	9.5	1.24	11.4
7	0.83	9.2	1.22	11.5
8	0.81	9.1	1.21	11.4
9	0.81	8.1	1.19	11.7
10	0.82	8.5	-	-
11	0.82	7.8	-	-

4. *IMC* CONTROLLER

The control objective is to reach and stay in the setpoint as quick as possible. In this sense, the effects of external disturbances and variations at system parameters should be efficiently attenuated.

The *IMC* controller design has the advantage of considering the internal model of the process. By assuming that the system operates in a closed-loop form, this control strategy makes it possible to mitigate the influence of variations and disturbances cited above.

The adopted *IMC* structure is shown in Fig. 7.

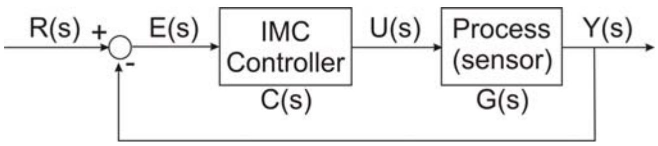

Fig. 7. *IMC* control structure arranged like a conventional feedback structure.

It turns out that for a simple first order linear system, the *IMC* controller results in a *PI* controller whose zero cancels open loop pole, i.e.

$$C(s) = K_P + \frac{K_I}{s} = K_P \frac{s + (K_I / K_P)}{s} \qquad (13)$$

By choosing $K_P = C_{th}/\tau_f$ and $K_I = G_{th}/\tau_f$ (where τ_f is the time constant of the *IMC* low pass filter), one has:

$$C(s)G(s) = \frac{C_{th}s + G_{th}}{\tau_f s} \frac{1}{C_{th}s + G_{th}} = \frac{1}{\tau_f s} \qquad (14)$$

and the following closed loop transfer function:

$$\frac{Y(s)}{R(s)} = \frac{1}{\tau_f s + 1} \qquad (15)$$

4.1. Experimental results

To compare the performance of linearized and non-linearized systems, two *PI* controllers have been implemented: one for each system. For the non-linearized system, a linear approximation around a specific operation point (*70ºC*) has been made. The results for the following test conditions are presented:

(i) Setpoint increasing by five steps of *10ºC*, varying from *50ºC* up to *90ºC*, step duration of *60s*, closed loop time constant=*5s* (Fig. 8);

(ii) Single setpoint by single step (*70ºC*), duration of *60s*, closed loop time constant=*5s* (Fig. 9).

It can be seen that both controllers could drive the temperature to the setpoint. However, in the non-linearized system overshoot occurs for all temperature steps, as well as for the designed operation point. Similar behaviour is observed in [10].

Considering the linearized system, by adjusting the system response curves using the least squares method, for each temperature step (Fig. 8), it was possible to calculate the time constants for each step. These values are shown on Table 2.

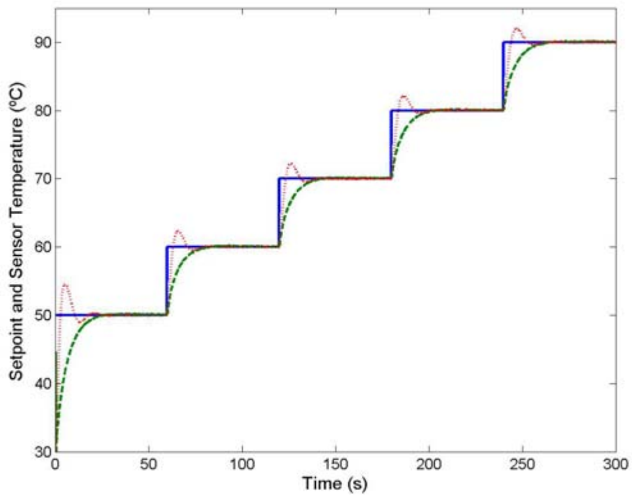

Fig. 8. Setpoint in increasing steps (continuous line), output of linearized system (dashed line) and output of non-linearized system (dotted line) with closed loop time constant=*5s*

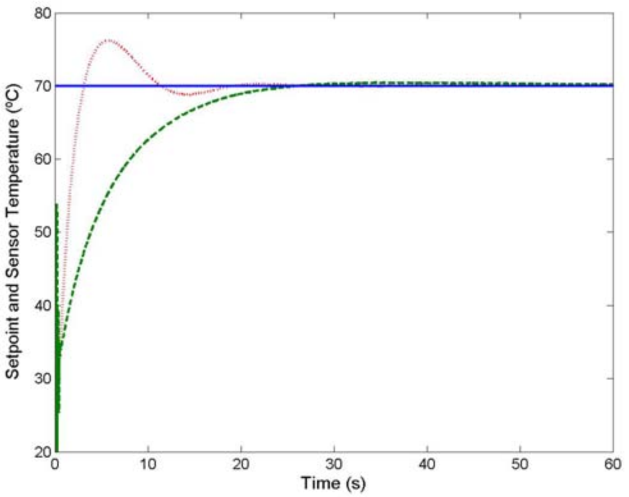

Fig. 9. Setpoint (continuous line), output of linearized system (dashed line) and output of non-linearized system (dotted line) with closed loop time constant=*5s*

Table 2. Calculated time constant for linearized system with setpoint in increasing steps and designed closed loop time constant for 5s.

Setpoint (ºC)	Time constant (s)	Variation of time constant projected (%)
50	4.48	-10.4
60	5.41	+8.2
70	5.78	+15.6
80	5.92	+18.4
90	6.00	+20.0

Other different tests of the controller using several closed-loop time constants have been done. The system behaves similarly as for the *5s* time constant. The results for the closed time loop constant designed for *0.5s* are shown in Fig. 10, Fig. 11 and Table 3. The tests conditions are:

- Setpoint increasing by five steps of *10ºC*, varying from *50ºC* up to *90ºC*, step duration of *10s* (Fig. 10);
- Single setpoint by single step (5*0ºC*), duration of *10s*, (Fig. 11).

Variations between the designed and the calculated time constants have been observed. Some of the reasons for this difference could be:

(i) The expected pole-zero cancellation from the project of *IMC* controller is not precise;

(ii) The determination of the time constant depends on a curve fitting.

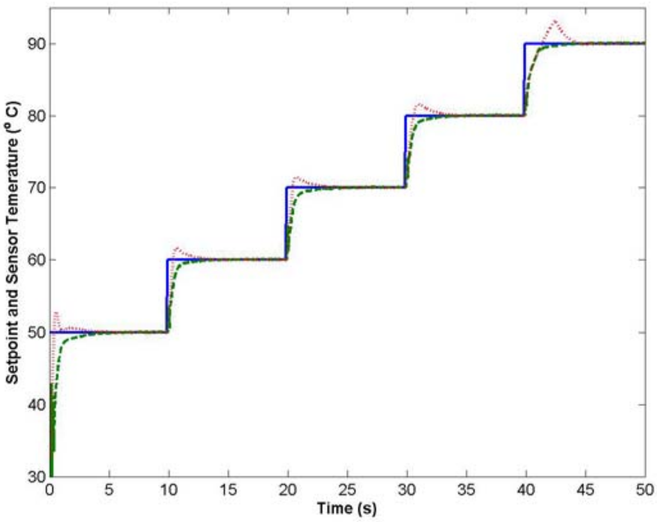

Fig. 10. Setpoint in increasing steps (continuous line), output of linearized system (dashed line) and output of non-linearized system (dotted line) with closed loop time constant=*0.5s*

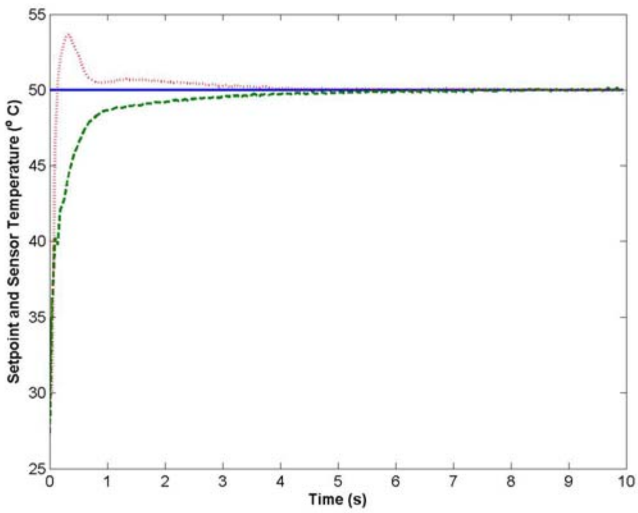

Fig. 11. Setpoint (continuous line), output of linearized system (dashed line) and output of non-linearized system (dotted line) with closed loop time constant=*0.5s*

Table 3. Calculated time constant for linearized system with setpoint in increasing steps and designed closed loop time constant for 0.5s.

Setpoint (ºC)	Time constant (s)	Variation of time constant projected (%)
50	0.44	-12
60	0.45	-10
70	0.47	-6
80	0.48	-4
90	0.55	+10

5. CONCLUSIONS

In this work, the direct use of electrical power as excitation parameter is proposed. This is due to the feedback linearization applied to the system, which also contributes for the characterization of sensor parameters in a single set of experimental test.

The *PI* controller designed by *IMC* technique was able to meet the imposed performance requirements The results for the linearized system showed to be better when compared to the non-linearized system.

As perspective for future woks we could mention:

(i) The use of feedback linearization to characterize other kinds of thermoresistive sensors;

(ii) The application of another control strategy in combination with feedback linearization;

(iii) The use of the measurement system developed to measure physical variables.

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