Automatic Dynamic Range Adjustment of a Controlled-temperature Thermoresistive-based Anemometer

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Abstract – **The thermoresistive-based hot-wire anemometer operating at a controlled temperature is a classical architecture that is vastly found in the literature. Nevertheless, this architecture presents a problem due to dynamic range variation with respect to the fluid temperature. In this work an alternative architecture of a controlled temperature anemometer with automatic adjustment of the dynamic range is proposed. Simulations of the proposed system using the parameters from a commercial sensor are presented and compared with the results from a classical configuration.**

Keywords - Anemometers; fluid velocity; thermoresistive sensors; hot-wire, controlled current source, dynamic range.

1. INTRODUCTION

Thermoresistive sensors can be employed in feedback structures for the measurement of temperature, incident radiation or fluid velocity. These circuits are based on the electrical equivalence principle where the measurand can be substituted by an electrical quantity. For the thermoresistive sensors, the thermal power variation due to variations in the temperature, incident radiation or fluid velocity variations is equivalent to the variation of electric power due to the Joule effect [1].

Hot-wire anemometers are based on thermoresistive sensors heated to a (almost) constant temperature. They are normally employed on the measurement of fast varying velocity or turbulent fluids for they present good sensitivity and small time constant with respect to other type of anemometers [2].

The classical hot-wire thermoresistive anemometer architecture is the Constant Temperature Anemometer (CTA), shown in Fig. 1. In this architecture, the sensor is employed in one of the arms of a balanced Wheatstone bridge and the other arm operates with fixed resistors. Any variations of the measurand, fluid velocity in this case, will tend to unbalance the bridge, causing the operational amplifier to vary its output to change the electric power dissipated by the thermoresistive sensor, balancing the bridge again. This architecture guarantees the sensor to operate at a constant (or practically constant) temperature and has the advantage of reducing the time constants associated with the measurement [3,4].

On the other hand, the CTA architecture has the disadvantage of varying the configuration output voltage dynamic range with the fluid temperature. The decrease of the dynamic range with respect to its maximum value will cause a reduction of the electrical signal sensitivity with respect to the measurand and also loss of resolution, since the ADC input range will not be fully used [5].

In this work we propose an architecture that provides automatic adjustment of its output voltage dynamic range and also employs control of the temperature in order to reduce the measurement system time constants.

2. THEORETICAL BACKGROUD

The classical CTA architecture is revised here exposing its disadvantage with respect to output voltage dynamic range variation. From the first law of thermodynamics, disregarding the incident radiation, the equation of Thermoresistive sensor can be written as

$$P_e = \frac{V_s^2}{R_s} = hS(T_s - T_a) + mc\frac{\partial T_s}{\partial t}, \qquad (1)$$

where P_e and V_s are the electrical power and voltage on the sensor; $R_{s,}$ m, c and S are respectively the resistance, the mass, the specific heat and the surface area of the sensor; T_s and T_f are respectively the sensor and fluid temperature (given in °C) and h is the global heat transfer coefficient to the surrounding, which is given by

$$h = a + b\vartheta^n, \qquad (2)$$

where ϑ is the fluid velocity and a e b are constants that can be determined experimentally.

For a thermoresistive sensor of the PTC (Positive Temperature Coefficient) metallic type, the relationship

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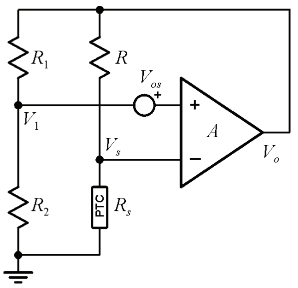

Figure 1. Schematic diagram of the CTA Architecture - constant temperature anemometer employing a Wheatstone bridge.

between its resistance and its temperature is approximately given as

$$R_s \approx R_0(1+\beta T_s), \tag{3}$$

where R_0 is the resistance of the sensor to 0 °C and β is the temperature coefficient.

A. Constant–Tempeture Anemometer Architeture

The CTA architecture makes the sensor temperature, in steady state, to be practically constant. For the CTA configuration shown in Fig. 1, in steady state and making $P_e = V_s^2 / R_s$, (1) can be written as

$$V_s^2 = R_s hS\left(T_s - T_f\right), \tag{4}$$

where R_s and T_s are supposed to remain essentially constant. Eq. (4) exhibits a nonlinear relation between the voltage across the sensor (V_s) and the measured.

The CTA architecture employs an operational amplifier that is modeled in steady state with an input offset voltage, V_{os}, and open-loop gain A. The output voltage of the operational amplifier is then

$$V_o = A\left(V_1 - V_s + V_{os}\right), \tag{5}$$

with

$$V_s = V_o / K,\, K = \left(R_s + R\right)/R_s \,. \tag{6}$$

Rewritten (5) and (6) for V_s gives

$$V_s = \left(\frac{A-K}{AK}\right)V_o + V_{os} \cdot \tag{7}$$

Substituting (7) in (4), gives

$$\left(\left(\frac{A-K}{AK}\right)V_o + V_{os}\right)^2 = R_s S(a+b\vartheta^n)\left(T_s - T_f\right) \cdot \tag{8}$$

The solution of (8) for V_o for positive voltage values, gives

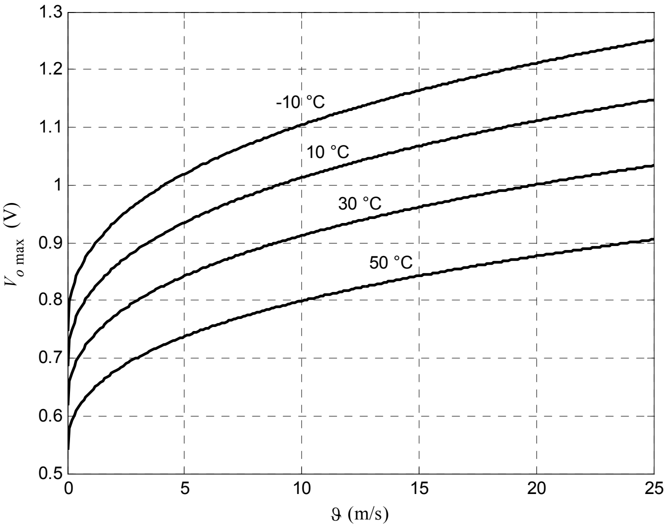

Figure 2. CTA output voltage as function of the fluid velocity for several values of the fluid temperature.

$$V_o = AK\frac{(-V_{os} + \sqrt{R_s Sh(T_s - T_f)})}{A-K}. \tag{9}$$

As it can be observed from (9), the configuration output voltage is also dependent on the fluid temperature. Simulations for typical sensor parameters, considering the fluid temperature varying from -10 to 50 ºC, were carried out and the output voltage curves as function of the fluid velocity are shown in Fig. 2. The maximum output voltage varies around 30 % for this temperature span.

3. PROPOSED ARCHITECTURE

The proposed architecture is based on a controlled current source for exciting the thermoresistive sensor and is shown in Fig. 3. An analysis of this configuration is carried out here to verify and compensate the influence of the fluid temperature and on the output voltage.

In Fig. 3, the thermoresistive sensor is excited by a controlled current source and the resulting voltage over the sensor is converted to digital by an analog-to-digital converter (A/D). The sensor voltage is used by the controller to generate a control signal to the current source, for accelerating the

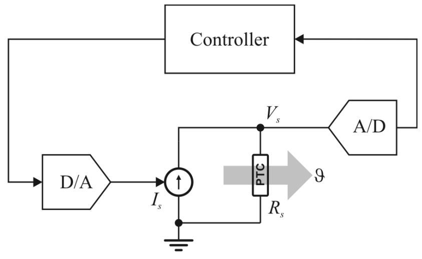

Figure 3. Temperature-controlled anemometer based on a controlled current source.

sensor thermal system dynamics, primarily, and for compensating the influence of the fluid temperature variations on the voltage output dynamic range.

For the electric power as $P_e = R_s I_s^2$, the sensor resistance in steady state can be written as

$$R_s = \frac{h\,SR_f}{h\,S - R_0\,\beta\,I_s^2}, \tag{10}$$

where R_f is the value of the sensor resistance at the actual fluid temperature, given by

$$R_f = R_0\left(1 + \beta T_f\right). \tag{11}$$

For an exciting current I_s, the sensor voltage is given by

$$V_s = I_s R_s = \frac{h\,SI_s R_f}{h\,S - R_0\,\beta\,I_s^2}. \tag{12}$$

B. Current feedback control

Fig. 4 shows the model of the anemometer architecture excited by a controlled current source. The sensor resistance R_s is calculated from the value of the sensor voltage V_s, knowing the exciting current I_s. The sensor resistance is compared with a reference resistance, R_r, and the resistance difference is used by controller for generating the current signal to excite the sensor. As the controller has the main objective to modify the system dynamics, making it faster, it can be a simple proportional controller.

For simplifying calculations, the current control signal is defined by

$$I_s = \sqrt{K_P\left(R_r - R_s\right)}. \tag{13}$$

For this configuration, from (13) and (10), the sensor resistance can be found as

$$R_s = \frac{C_f + R_r BK_P - A}{2BK_P}. \tag{14}$$

With

$$C_f = \sqrt{R_r^2 B^2 K_P^2 + \left(4R_f - 2R_r\right) ABK_P + A^2}, \tag{15}$$

$$A = hS,\ B = R_0\beta.$$

Substituting (14) in (13), the sensor current can be determined by

$$I_s = \sqrt{\frac{R_r BK_P + A - C_f}{2B}}. \tag{16}$$

The output voltage is obtained multiplying (16) and (14) as

$$V_s = \frac{R_r BK_p - A + C_f\sqrt{\dfrac{R_r BK_p + A - C_f}{B}}}{2BK_p\sqrt{2}}. \tag{17}$$

Equation (17) gives the sensor voltage as function of the fluid speed. However, for the controlled-current architecture, this voltage is still dependent on the fluid temperature through C_f. This dependency can be observed in Fig. 5, for the sensor voltage as a function of the fluid speed, and for different values of the fluid temperature varying from -10 to 50 ºC. For this fluid temperature range, the sensor voltage for the maximum speed varies around 37 % with respect to its maximum overall value.

C. Adjusting for the maximum dynamic range

In order to assure the maximum output voltage dynamic range, i.e., keeping the sensor voltage constant in its maximum value for the maximum fluid velocity, the system must somehow compensate the influence of the temperature in (17). A suitable way for providing this is to adjust the reference resistance, R_r, as function of the fluid temperature. However, it must be ensured that the rate of variation of the adjustment is

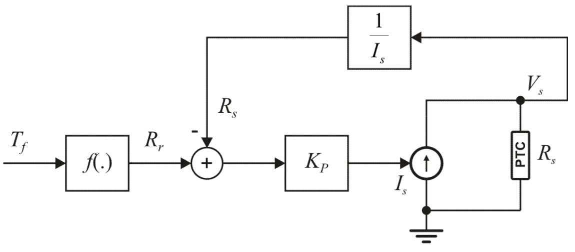

Figure 4. Sensor output voltage dynamic range adjustment model.

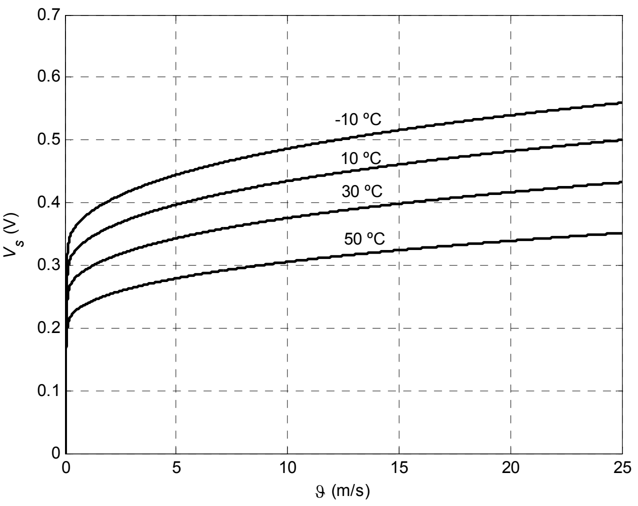

Figure 5. Controlled current anemometer output voltage as function of the fluid velocity for several values of the fluid temperature.

$$R_r = \frac{\sqrt{\frac{4V_{s\max}^2 B}{A} + R_f^2}}{2} + \frac{R_f}{2} - \frac{R_f A^2 \sqrt{\frac{4V_{s\max}^2 B}{A} + R_f^2}}{2V_{s\max}^2 B^2 K_P} + \frac{A}{BK_P} + \frac{R_f^2 A^2}{2V_{s\max}^2 B^2 K_P}. \qquad (18)$$

much slower than that of the current control, so no restrictions is imposed to the temperature controller.

Considering that for the maximum fluid velocity the sensor voltage is constant, given by $V_{s\max}$, i.e. for providing a constant output voltage dynamic range, (17) can be solved for the reference resistance, given (18).

For a high controller gain, $K_P \geq 1$, the last three terms of (18) can be disregarded with respect to the two first terms, because they are at least 2 orders of magnitude smaller. Thus, this equation can be simplified to be

$$R_r = \frac{R_f + \sqrt{\frac{4V_{s\max}^2 B}{A} + R_f^2}}{2}. \qquad (19)$$

Considering that for a given fluid temperature (that could be for instance its minimum value) T_{f0} one has a given resistance reference value, R_{r0} and that $R_{f0} = R_f(T_0)$, $V_{s\max}$ can be found as

$$V_{s\max}^2 = \frac{AR_{r0}^{\ 2} - AR_{f0}R_{r0}}{B}. \qquad (20)$$

Substituting (20) in (19) gives

$$R_r = \frac{R_f + \sqrt{4R_{r0}^{\ 2} - 4R_{f0}R_{r0} + R_f^{\ 2}}}{2}. \qquad (21)$$

With $R_f = R_0\left(1+\beta T_f\right)$ and $R_{f0} = R_0\left(1+\beta T_{f0}\right)$. On the other hand, R_{r0} is a design parameter that can be determined as function of the sensor parameters, in order to obtain a desired output voltage span.

4. SIMULATION RESULTS

All simulations in this work have been carried out using the sensor parameters given in Table I.

The value of R_{r0} was determined for yielding a sensor temperature of around 88 ºC for a fluid temperature of -10 ºC (98 ºC above the fluid temperature) and gives a maximum output voltage of around 0.56 V. The controller gain was set to $K = 1$. The parameters specifically for the current controlled anemometer are shown in Table II.

In Fig 6, the output voltage of the controlled current configuration with automatic adjustment of the dynamic range is shown as function of the fluid velocity, for the values of the fluid temperature of -10, 10, 30 and 50 ºC.

The adjustment is not exact because it is carried out using an approximate equation. In Fig. 7, the variation of the sensor voltage with the fluid temperature is shown detailed. It can be observed that, in this case, the sensor voltage for the maximum fluid velocity varies only around 0.1 % w.r.t its maximum overall value, which does not compromises the dynamic range.

The sensor temperature is shown as function of the fluid velocity for different fluid temperatures in Fig. 8. As it can be observed from this figure, the sensor temperature varies little with the fluid velocity, but significantly with the fluid temperature.

If Fig. 9, the proposed configuration output voltage response to a fluid velocity step, from 0 to 10 m/s, is shown, for the proportional controller gain of 1. For this gain value, time constant is around 0.15 ms.

5. CONCLUDING REMARKS

In this work a new controlled-temperature anemometer architecture with the sensor excited by a controlled current source and with automatic adjustment of the dynamic range was proposed. This architecture is suitable for the cases where the fluid temperature is expected to vary, and where classical architectures present the disadvantage of varying their output signal dynamic range.

The proposed architecture provides control of the sensor temperature, in order to modify the system's dynamics and to reduce the associated measurement time constants, and adjustment of the temperature operating point for ensuring the maximum output voltage dynamic range.

Simulations results using parameters from a real

TABLE I. SENSOR PARAMETERS

S	94 x 10^{-9} m^2
mc	7 x 10^{-6} J ºC^{-1}
β	0,00385 ºC^{-1}
R	4,96 Ω
R_0	3,5 Ω
a	2375 W/m^2.°C
n	0,5
b	976 W/m^2.°C
T_{fmin}	-10 °C

TABLE II. CONTROLLED CURRENT ARCHITECTURE PARAMETERS

R_{s0}	4.7 Ω
R_{f0}	3.365 Ω
T_{f0}	-10 °C
T_{s0}	137.08 °C
$V_{s\max}$	0.55 V
K_p	1

commercial thermoresistive sensor have shown that, for a fluid temperature span from -10 to 50 ºC, the output voltage dynamic varies only 0.1 %. This result can be contrasted with results from simulations using a classical constant-temperature anemometer employing a Wheatstone bridge, which exhibit a dynamic range variation of around 30 %.

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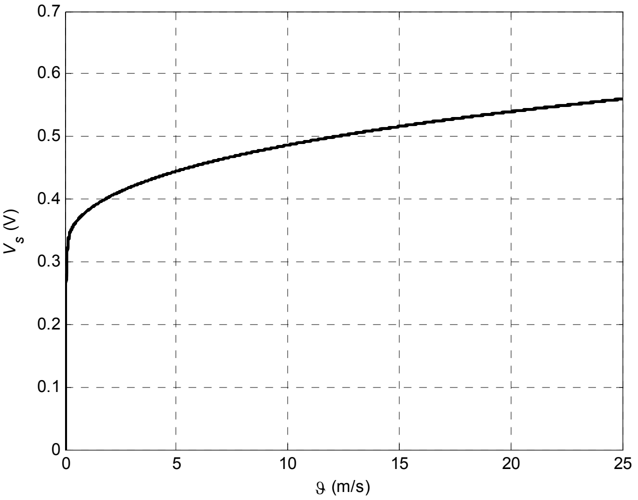

Figure 6. Controlled-current anemometer output voltage with dynamic range adjustment as function of the fluid velocity for several values of the fluid temperature.

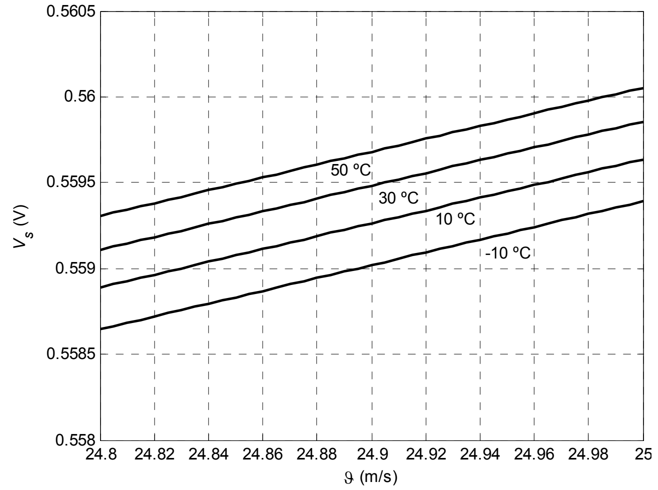

Figure 7. Detail of the graph of Figure 6, showing variation on the configuration output voltage.

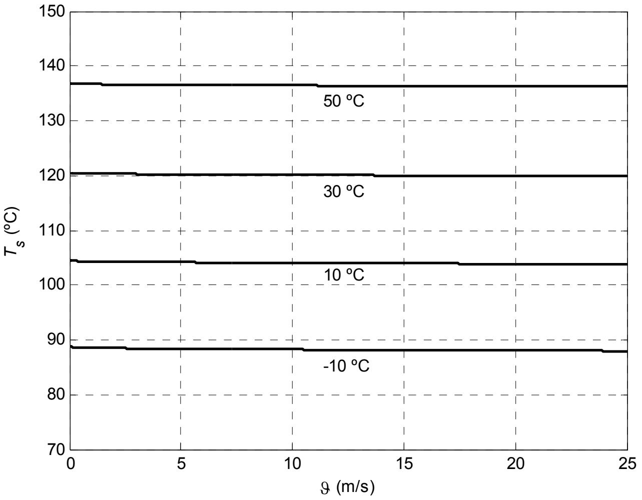

Figure 8. Sensor operating temperature as function of the fluid velocity for several values of fluid temperature.

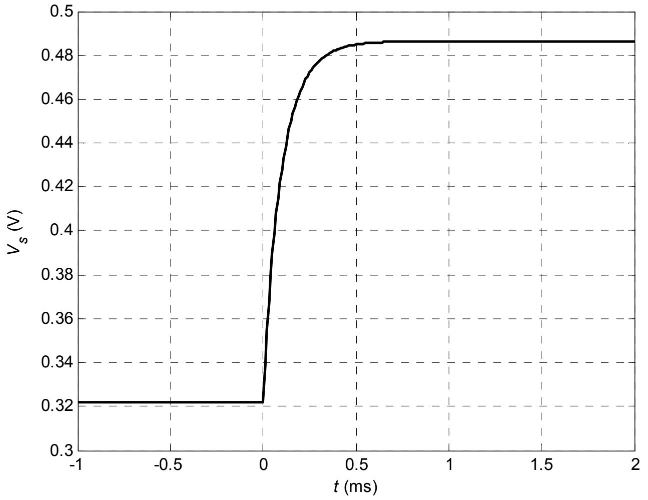

Figure 9. Contolled-current anemometer output voltage for a fluid velocity step variation, from 0 to 10 m/s.