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THE ANALOG SIGNAL PROCESSING IN MEASURING SYSTEMS WITH A SINGLE PASSIVE SENSOR

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Abstract: The quality of a measuring system depends more and more on the first stages of the measuring chain i.e. the sensor and the primary signal conditioning circuit. The use of a high resolution A/D converter at the very beginning of that chain is generally correct. In practice however, sensors are mainly analogue and they need some analogue signal conditioning circuits. The paper deals with the analogue signal processing in the circuits with a single passive sensor. Uncertainty, error elimination and a nonlinearity of some essential structures have been analysed. The general conclusions may be formulated as follows: Extremely simple methods of analogue signal processing lead to quite good results but some limitations have to be respected. The passive sensor parameter which determines almost all limitations is the ratio $ÄR_X/R_0$.
Keywords: Passive sensors, analogue signal conditioning

1 INTRODUCTION

The tendency for reduction of the electronic analogue equipment and to performing an A/D conversion at the very beginning of the signal-conditioning path, dominates in the design of measuring transducers. In some cases the A/D conversion is performed just in the sensor, like in the digital line and disc encoders. At the frequency output sensors the conversion to the digital signal is extremely simple and needs only a counter. All other sensors with electrical output need some analogue circuits to transform the output sensor variable into the DC voltage appropriate for A/D conversion. In the case of active sensors such as thermoelectric and thermopiles sensors, piezoelectric accelerometers, photovoltaic sensors etc, the only task of the analogue signal conditioning circuit is to amplify the signal to the level high enough for an A/D converter taking into account the required accuracy, stability and noise protection. The A/D converter is either separate or integrated with the sensor on the same chip. In the case of passive sensors like thermoresistors, photoresistors, strain gages, piezoresistors, capacitive and inductance displacement sensors, humidity sensors and many others, some additional problems appear, related to the necessity of cutting off the initial offset value corresponding to the initial (or zero) value of the measured quantity. Such a cutting-off process may be performed either in the analogue part of the electronic circuit or by an appropriate algorithm after the A/D conversion. The algorithm method looks to be more effective especially if the cutting–off algorithm is a part of other digital signal conditioning. Error and uncertainty analysis indicates however, that better results may be sometimes achieved if some tasks of the system, like span extracting and linearisation are performed rather in an analogue than in a digital way.

The paper explains when is the case and forms some general rules how to do it.

2 ERRORS AND UNCERTAINTY PROPAGATION.

The analysis of each measuring structure depends on the examination of the measurement function $V_{out} = F(V_S, V_1, V_2, ...V_i, ...V_k)$ in order to determine the errors and uncertainty propagation rules. V_S is the sensor variable and V_i are all the other variables influencing the output variable $V_{out.}$ First of all one has to distinguish between errors and uncertainties. According to their definition, errors are the differences between the actual value and the correct or nominal value. The law of error propagation describes how the errors of all variables V_i and V_S influence the error of the output variable V_{out} of the system. Such an analysis is a basis for error compensation and error correction procedures. For the purpose of that paper only additive E^A and multiplicative E^M errors will be considered. Other kind of errors like higher order errors and interaction errors will be neglected. Multiplicative errors are considered for sensors parameters V_S only, because in the measurement function all other variables have nominally constant values and therefore there is no need to introduce their multiplicative errors to the performed analysis. The basic relation for the errors propagation is then

$$e_{out}=\frac{E_{out}}{V_{out}}=\frac{\partial V_{out}}{\partial V_S}\frac{E_S}{V_{out}}+\sum_{i=1}^{k}\frac{\partial V_{out}}{\partial V_i}\frac{E_i}{V_{out}}=\frac{\partial V_{out}}{\partial V_S}\frac{e^A V_{S0}}{V_{out}}+\frac{\partial V_{out}}{\partial V_S}\frac{e^M V_S}{V_{out}}+\sum_{i=1}^{k}\frac{\partial V_{out}}{\partial V_S}\frac{E_S}{V_{out}} \qquad (1)$$

where E are absolute and å are relative errors.

Uncertainties consist of uncompensated and uncorrected parts of all variables mentioned above as well as by other variables which are neither controlled nor specified in the deterministic measurement model and are represented by noises [3]. Uncertainties are always random and therefore their law of propagation is based on the variance additions rule.

$$\pm d_{out}=\pm\sqrt{\left(\frac{\partial V_{out}}{\partial V_S}\frac{V_S}{V_{out}}d_S^2\right)^2+\sum_{i=1}^{K}\left(\frac{\partial V_{out}}{\partial V_i}\frac{V_i}{V_{out}}d_i^2\right)^2} \qquad (2)$$

where δ_i and δ_s are standard deviations related to all elements of the measuring system and the sensor parameter, respectively. All these standard deviations components include both environmental and inherent noises. In order to obtain the uncertainty limits, the standard deviation has to be multiplied by a factor (enhance factor commonly equal to 2 or 3) according to the expected level of confidence [6]. In that paper however, the δ values are treated as uncertainties themselves. The derivatives present in both equations (1) and (2) indicates the sensitivities to the changes of the variables V_S or V_i and are termed in this paper as errors or uncertainty multiplication factors K.

3 THE ANALYSIS OF MEASURING STRUCTURES.

Each passive sensor is characterised by a parameter sensitive to the measured quantity (resistance, capacity, mutual impedance or other).Such a parameter always consists of two parts: R_0 and R_X, where only R_X depends on the measured quantity X. (Symbol R is taken arbitrary) For the purpose of that paper two relative coefficients have been introduced: The firs one is $r(x) = R_X/\Delta R_X$ where ΔR_X is the span of the sensor sensitive parameter corresponding with the ΔX span of the measured quantity. The r(x) represents the level of the actually measured quantity and changes its value from 0 to 1.

The other, and more important coefficient is defined as $m = \Delta R_X/R_0$. The "m" value depends on the used sensor. In the strain gage sensors "m" is very small, about $2*10^{-3}$, in capacitive humidity sensors -approximately 10^{-1}, and in Pt 100 RTD's reaches up to 3.5. Errors and uncertainties related to the whole sensor parameter $R_0 + R_X$ become much greater when related to the part R_X of the sensor and then to the measured variable X. Hence the "natural" multiplication factor K which appears in propagation laws is equal to 1/m, and for sensors with low level of "m" reaches non acceptably high values.

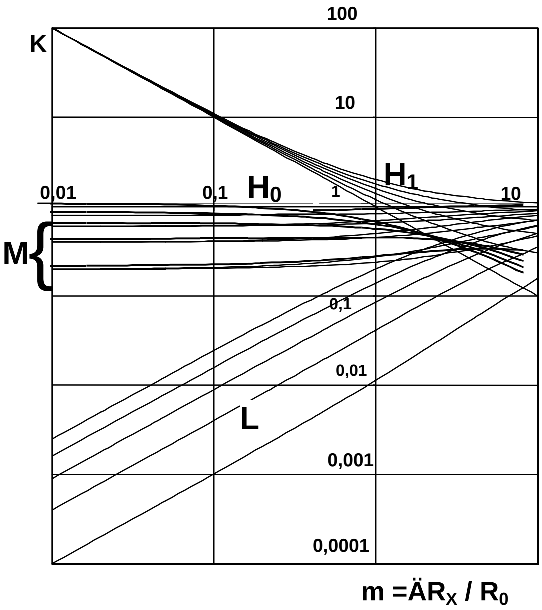

Figure 1. Error multiplication factors

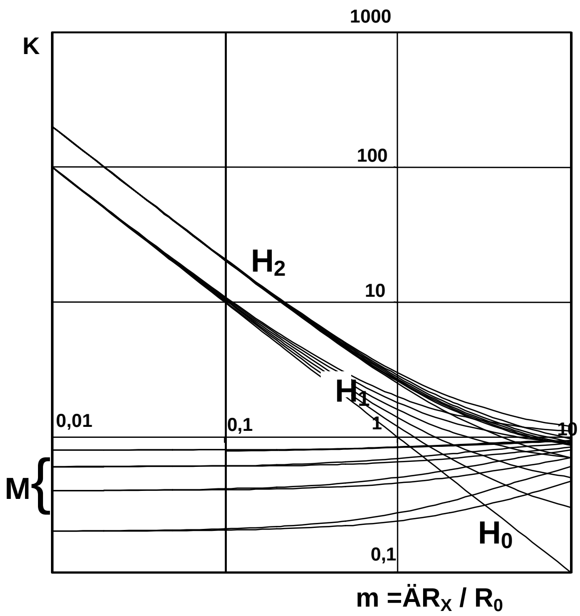

Figure 2. Uncertainty multiplication factors

A proper choice of the measuring structure leads sometimes to the reduction of the multiplication factors for some components of errors and uncertainties. Three kinds of structures described below have been analysed: nondifferential, differential and quasi-differential structure. The results are presented in the form of the multiplication factor K related to each error or uncertainty component. The K factor value depends on the m coefficient (Fig. 1 and 2). In order to simplify the presentation, the K-factors are gathered into groups H and M (Tables 1 and 2, Figures 1 and 2). If the K-factor belongs to the group H (high) , the related error or uncertainty either preserves its inconvenient 1/m value (H_0) or even is slightly enhanced (H_1 or H_2).

Table1. Classification of the error multiplication factors

Structure/ Figure	$å_I$ ($å_V$)	$å_{I1}$	$å_A$	$å^A_R$	$å^M_R$	$å_{R1}$	$å_{No}$	Remarks
Nnondiffer. / 3a	H	-	H	H_0	H	-	H_0	-
Reference. / 3b	0	-	H	M	H	0	H_0	$å^A_R = å_{R1}$
Differential / 4a.	M	0	M	0	M	0	-	$å_I = å_{I1}$, $å^A_R = å_{R1}$
Switched cap./ 4b	M	-	M	0	M	0	-	$å^A_R = å_{R1}$
Current bridge / 5a	M	-	M	L	M	-	-	$å^A_R = å_{R2} = å_{R3} = å_{R4}$
Voltage bridge / 5b,5c	M	-	M	M	0	-		-

Table 2. Classification of the uncertainty multiplication factors.

Structure / Figure	$ä_I$ ($ä_V$)	$ä_{I1}$	$ä_A$	$ä_R$	$ä_{R1}$	$ä_{No}$
Nondifferential / 3a.	H_1	-	H_1	H_0	-	H_0
Reference / 3b	0	-	H_1	H_0	H	H_0
Differential / 4a	H_0	H_1	M	H_0	H_0	-
Switched cap. / 4b	M	-	M	H_0	H_0	-
Current bridge / 5a	M	-	M	H_2	-	-
Voltage bridge /5b, 5c	M	-	M	H_2	-	-

If the K-factor belongs to the group M , the related error or uncertainty is reduced to the multiplicative component only. The K value equal to zero indicates that the structure eliminates the related error or uncertainty completely. The group L (low) is created specially for current supplied bridges and will be discussed later. Tables 1 and 2 summarises the results of the analysis in a form of K-factors classification for each errors and uncertainties component.

3.1 Nondifferential structure

The simplest non-differential structure consists of a current source, sensor, amplifier and A/D converter (Fig. 3a).

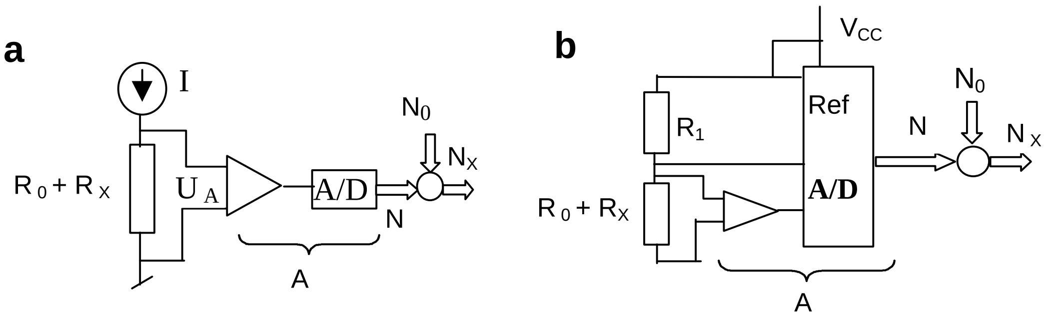

Figure 3. Basic nondifferential structures.

The numerical value N_x corresponding to the measured value X is obtained by the numerical subtraction $N_x = N - N_0 = IA(R_0 + R_X) - N_0$, where N_0 is a constant value corresponding to the R_0 value of the sensor. The coefficient A represents both the amplification factor and the conversion coefficient of the A/D converter. For that structure the K coefficients related to all variables belong to the group H and it means that the structure is extremely sensitive to all errors and uncertainties especially if the used sensor has a low value of m coefficient. The better results may be achieved by the use of an A/D converter with the reference input (Fig. 3b.). For that structure $N = A\frac{U_A}{U_{R1}}$ and the measurement function is then $N_X = A\frac{R_0 + R_X}{R_1} - N_0$. Both errors and uncertainties due to the supply current are eliminated. Furthermore, if both elements R and R_1 have the same additive errors, the addative error $å^A_R$ is transferred to miltiplicative errors (group M) and become many times lower.

3.2 Ideal differential structures

Two basic analogue differential structures are presented in Fig. 4a and 4b. Matching $R_0 = R_1$ and $I = I_1$ enables to cut off the offset voltage IR_0. It is well known that the ideal differential structure eliminates additive errors and preserves multiplicative errors. Really, by $\mathring{a}_I = \mathring{a}_{I_1}$ and $\mathring{a}_R^A = \mathring{a}_{R_1}^A$, all errors are reduced to the multiplicative components only.

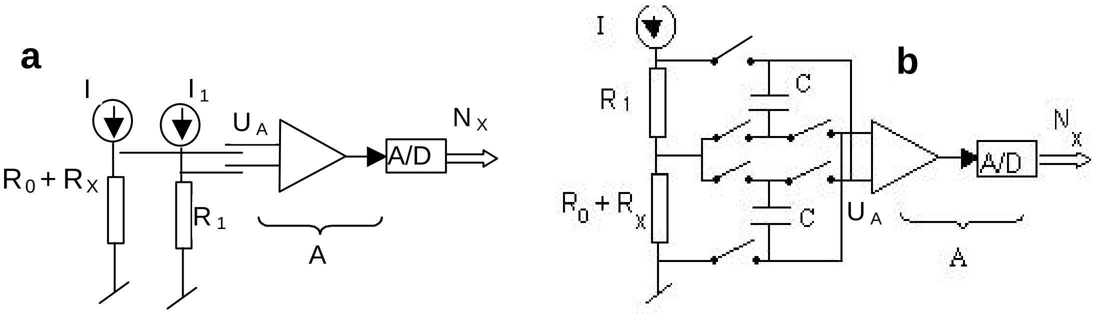

Figure 4. Examples of two basic differential structures, with current sources (a) and with switched-capacitors circuit (b).

Comparing the results for differential and nondifferential structures it is worth noticing that in all differential structures the part of uncertainty related to the amplifier ä$_A$ is transferred to the multiplicative component and is not multiplied by the 1/m factor, but by the r(x) coefficient, which does not exceed the value of 1. In many practical cases that part is a dominating one in the whole uncertainty [1] and therefore the property mentioned above is a great advantage of the differential structures. From that point of view, the structure presented in Fig. 4b is even better because not only uncertainty ä$_A$ but also ä$_I$ are reduced to the multiplicative component (Table2).

3.3 Quasi-differential structures

Unbalanced bridges used very often in signal conditioning circuits belong to quasi-differential structures. Three examples are presented in Fig. 5.

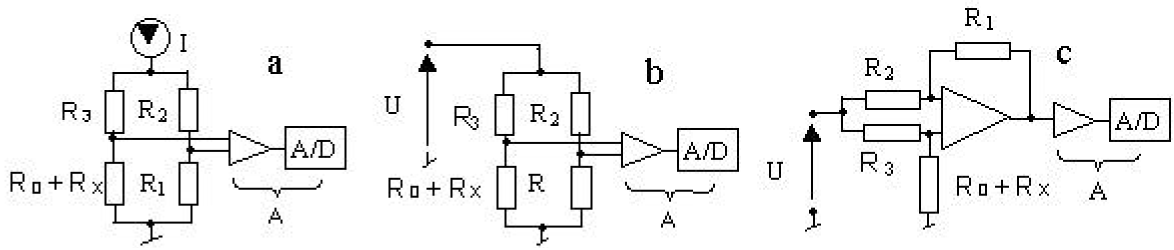

Figure 5. Unbalanced bridges, Current supplied (a), voltage supplied (b) and active bridge (c)

The calibration functions of unbalanced bridge circuits are nonlinear and, assuming $R_1 = R_2 = R_3 = R_0$ they may be expressed as follows for the examples 5a, 5b, and 5c, respectively:

$$N_{Xa} = AI\frac{R_X}{4(1+R_X/4R_0)}, \qquad N_{Xb} = AU\frac{R_X}{4R_0(1+R_X/2R_0)}, \qquad N_{Xc} = AU\frac{R_X}{2R_0(1+R_X/2R_0)} \qquad (3)$$

Nonlinearity is twice smaller for the current supplied bridge (a) than that for the voltage supplied bridges (b and c).

The Uncertainty propagation coefficients and abilities of errors compensation of semi-differential structures are different from those of ideal differential structures. It ought to be emphasised that in the bridge circuits the uncertainty is greater than that of the ideal differential structures, (H_2 is more then twice higher then H_0).In current supplied bridge the additive errors are reduced but not cancelled at all. The value of K for that errors is not equal to zero but belongs to the group L. The voltage supplied bridge however, cancels multiplicative errors which is observed neither in the ideal differential structures nor in the current supplied bridges.

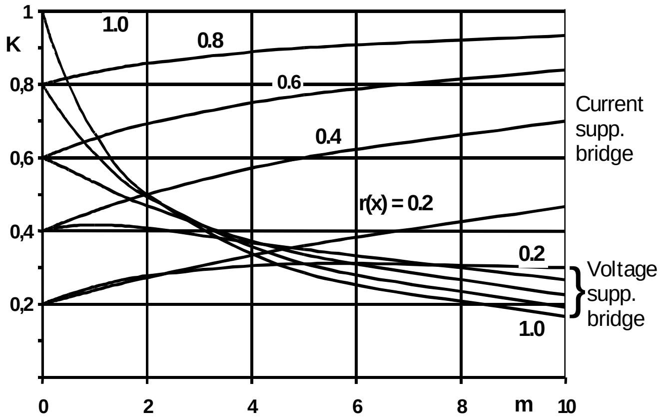

Figure 6. K- factor related to the multiplicative errors of bridge circuits (linear scale).

The most spectacular difference between the voltage supplied and current supply bridges consists in the propagation of multiplicative errors at higher values of m coefficient, m > 1 (Fig. 6). For the current supplied bridges the multiplication factor K remains practically constant, while for the voltage supplied bridges it rapidly falls down to the level of approximately 0.3, independently on r(x) value. In practice it means the three times reduction of multiplicative errors in the voltage supplied bridges with respect to the current supplied bridges. It is advantageous when multiplicative errors dominate.

4 NONLINEARITY REDUCTION

Nonlinear relation between the measured quantity X and the sensor output variable R_X is a rule. When the nonlinearity error å_N is low comparing to the uncertainty of the system, it may be neglected or included to the global uncertainty as one of its component. If not a case however, the nonlinearity error has to be reduced either by an appropriate numerical procedure or in the analogue way. Only those methods which belong to the analogue signal conditioning will be discussed here. The best method of analogue nonlinearity reduction is the use of two (or four) sensors of opposite nonlinearity in differential or quasi-differential structures [2] [3]. This method is commonly used in capacitance sensors and in piezoresistive pressure sensors, but in many other applications its performance is not possible because of technical reasons (temperature sensors, moisture sensors, gas sensors etc). In that cases two simple methods presented below may be used. The methods are different in their principles, but both lead to the same results because of the same mathematical model. The first method is based on the use of voltage controlled current sources in the structure presented in Fig 4a. The supply currents depend linearly on the output voltage $I = I_0\left(1+ \text{á}U_A\right)$.Linearisation is performed by the proper selection of the coefficient á according to the sensor nonlinearity. The relation between U_A and R_X is then nonlinear $U_A = \frac{I_0 R_X}{1+\text{á}\, I_0 R_X}$ and enables a successful linearisation of some kind of sensors nonlinearities. The nonlinearity is completely eliminated when the calibration curve of the sensor $R_X = f(X)$ may be expressed exactly as

$$\frac{R_X}{\text{Ä}R_X} = \frac{\frac{X}{\text{Ä}X}}{1+\text{á}\, I_0 \text{Ä}R_X\left(1-\frac{X}{\text{Ä}X}\right)} \qquad (4)$$

When the calibration curve only approximates the equation (4), nonlinearity is reduced, but not cancelled. Fig. 7 presents such sensor calibration curves which correspond to Eq. (4). It is evident that sensors with S-shaped calibration curve will not be effectively linearised by the discussed method.

The second method is even simpler, because it does not require the voltage controlled sources [4]. It depends on the proper choice of the Thevenin equivalent resistance R_{Th} seen from the sensor terminals, that is from the virtual terminals of the effective part of the sensor R_X. According to such a definition of R_{Th}, the R_0 component of the sensor belongs to R_{Th}. The method is based on the theorem that any voltage between two points of each linear electrical circuit containing one variable parameter R_X may be presented in a form

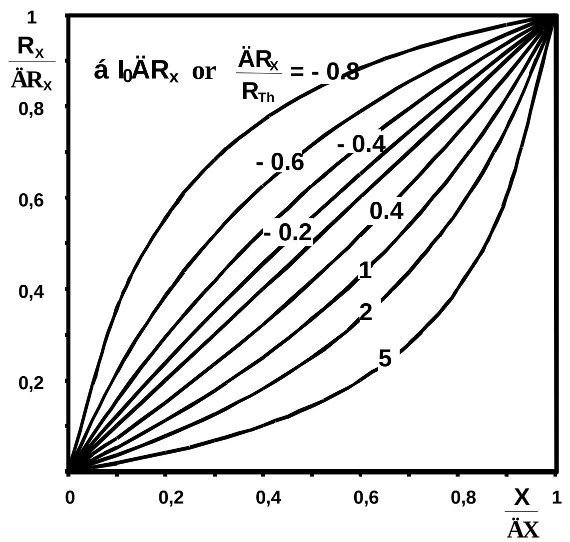

Figure 7. Sensors calibration curves linarisable by the proposed methods.

$$U = \frac{U_0 R_{Th} + U_\infty R_X}{R_{Th} + R_X} \qquad (5)$$

where U_0 is the voltage at $R_X = 0$, U is the voltage at the open circuit ($R_x =$). Taking into account that in differential structures $U_A = U_0 = 0$ at $R_X = 0$, one obtains the nonlinear relation

$$U_A = U_\infty \frac{R_X}{R_{Th} + R_X} . \qquad (6)$$

which may be used for linearisation of the sensors with the following calibration curves

$$\frac{R_x}{ÄR_x} = \frac{\frac{X}{ÄX}}{1 + \frac{ÄR_x}{R_{Th}}\left(1 - \frac{X}{ÄX}\right)} \qquad (7)$$

Equation (7) is exactly the same as Eq. (4), only the coefficient á $I_0 ÄR_X$ is replaced by $ÄR_X/R_{Th}$. It has to be emphasised that the second method involves no additional costs because it is realised by a proper matching of the circuits elements only. Very similar method is (probably) used in commercially available transducers like Burr-Brown IXR100 [7].

5 CONCLUSIONS.

1. The low value of "m" coefficient always results in the greater uncertainty and sensitivity to the influenced variables when using the passive sensors. It is a general rule, but some properties of the considered structures may be used to reduce that inconvenience.

2. Uncertainty analysis shows that even in the case of a single passive sensor, the analogue signal conditioning with the use of differential structures leads to the better results than a direct conversion of the sensor voltage drop to the digital signal. Moreover, the real resolution of such a direct conversion is $R_0/ÄR_X$ times lower than the resolution of the used A/D converter. For these two reasons the structure presented in Fig. 3a. should be avoided.

3. Structures, which realise the relation of sensor voltage to the reference voltage (Fig. 3b), are the only structures, which are able to cancel both the errors and uncertainties due to supply voltage or supply current. (Tables 1 and 2, column 2).

4. Properties of the pure differential and quasi-differential structures are not the same. Quasi – differential structures neither cancel additive errors nor preserve multiplicative errors. The differences between the structures are negligible at low values of the m coefficient but become serious at m > 1. Fig. 6 shows how to choose the structure with respect to the applied sensor (m value), measuring range and a kind of dominating errors.

5. It is highly recommended to check the effectivity of both simple linearisation methods presented in the paper, before making the decision about the numerical linearisation either by a look-up table method or by the calculation of inverse calibration function [5]. The low value of m gives also some limitations in application of the proposed methods, but fortunately, as a rule of a thumb, at the heavy nonlinear sensors the m coefficient is usually high.

5.6.Generaly the value of the m coefficient of the passive sensor determines the troubles which may be expected in the signal conditioning process.

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