XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

MINIMIZATION OF PRESSURE SENSORS TRANSFORMATION FUNCTIONS FOR A GIVEN MEASUREMENT ACCURACY

Ekaterina Lapina [1], Andrey Lapin [2]

[1] Department of Information-Measuring Engineering, Faculty of Computer Engineering, Control & Communications, South Ural State University, Chelyabinsk, Russian Federation, ekaterina.lapina@yahoo.com
[2] Department of Information-Measuring Engineering, Faculty of Computer Engineering, Control & Communications, South Ural State University, Chelyabinsk, Russian Federation, a_lapin@mail.ru

Abstract – The paper presents a brief analysis of works associated with the choice of transformation functions for smart pressure sensors. The notion of complexity factor and offer a way to assess the complexity of models for different types of transformation functions was given.

Keywords: pressure transducers (sensors), transformation function, smart pressure sensors.

1. INTRODUCTION

The improvement of the measurement accuracy of smart pressure sensors depends on the correct choice of the model transformation function (TF). In the last few years a number researches were carried out [1-3], to study this problem. Questions related to the complexity of models and the choice of TF in these researches seems to us insufficient. The connection between the measuring transducer graduation and construction of the simplest and cheapest TF, with the same accuracy, was not considered.

2. STATEMENT OF THE PROBLEM

Source information for the construction of a transformation function gained as the result of graduation [4] of the measuring transducer. The definite sequence of exemplary pressure values at different fixed temperature of environment are input to measuring transducer. Voltage, depending on the input pressure and temperature, measured at the output of the measuring transducer.

We will be studying the inverse two-factor model of TF built on the results of the graduation:

$$\mathrm{P} = \mathrm{F}^{-1}\big(\mathrm{U_p}(\mathrm{T}), \mathrm{T}\big) + \mathrm{e}, \quad (1)$$

where P – measured pressure, that was calculate based on inverse TF (P is input to measuring transducer); $\mathrm{U_p}$ – output voltage (depends on pressure); T – temperature of environment, in which measuring transducer is located; e – unrecorded factors (noise); F^{-1} – model of inverse TF .

Taking into account a specific assumption [5] model of inverse TF has the following form

$$\mathrm{P} = \sum_{\mathrm{N}=0}^{\mathrm{K_p}} \mathrm{B_N}(\mathrm{T})\big(\mathrm{U_p}\big)^{\mathrm{N}} + \mathrm{e}, \quad (2)$$

where P – measured pressure, that was calculate based on inverse TF (P is input to measuring transducer); $B_0(T) \dots B_{K_p}(T)$ – coefficients of model of inverse TF , as the function depending on temperature and known U_p; U_p - output voltage (depends on pressure). The coefficients $B_0(T) \dots B_{K_p}(T)$ can be written as a function depending on temperature following way

$$\mathrm{B_N}(\mathrm{T}) = \sum_{\mathrm{j}=0}^{\mathrm{K_T(N)}} \beta_{\mathrm{N,j}} \cdot \mathrm{U_T^j}, \quad (3)$$

where $\mathrm{K_T(N)}$ – value of the degree of polynomials (coefficients) included into the expression (2), $\mathrm{U_T}$ – voltage at the pressure measuring transducer output proportional to the ambient temperature, (channel temperature measurement), $\beta_{\mathrm{N},0} \dots \beta_{\mathrm{N},\mathrm{K_T(N)}}$ – coefficients of the polynomial $\mathrm{B_N}(\mathrm{T})$.

Parameters $\mathrm{K_T}$ и $\mathrm{K_P}$ defined by the number of graduation points for temperature $\mathrm{N_T} = \mathrm{K_T} + 1$ and for pressure $\mathrm{N_P} = \mathrm{K_P} + 1$. According to the recommendations of [6] agree that $\mathrm{N_T} = 6$ и $\mathrm{N_P} = 6$, т.е. model (2) will be:

$$\mathrm{P} = \mathrm{t} \cdot \beta' \cdot \mathrm{p}, \quad (4)$$

where $t = [t^0 \quad t^1 \quad \dots \, t^5]$ – a column vector sized (1×6).

The elements of this vector are t – normalized values of voltage at the output of measuring transducer, via temperature, calculated by the formula $t = \frac{U_T - U_{T_{min}}}{U_{T_{max}} - U_{T_{min}}}$; $p' = [p^0 \quad p^1 \quad \dots \, p^5]$ – transposed column vector sized (6×1). The elements of this vector are p – normalized values of voltage at the output of measuring transducer, via pressure, calculated by the formula $p = \frac{U_p - U_{p_{min}}}{U_{p_{max}} - U_{p_{min}}}$; β'– transposed matrix sized (6×6) is

$$\beta = \begin{bmatrix} \beta_0 & \dots & \beta_5 \\ \vdots & \dots & \vdots \\ \beta_{30} & \dots & \beta_{35} \end{bmatrix}; \quad (5)$$

or an upper triangular matrix sized (6×6) is

$$\beta = \begin{bmatrix} \beta_0 & \dots & \beta_5 \\ \vdots & \dots & \vdots \\ \beta_{20} & \dots & 0 \end{bmatrix}. \quad (6)$$

We believe that the more coefficients mathematical model comprises, more difficult it is. The simplest model contains only the coefficient β_0, the model is the most difficult (4)-(5), as it contains all 36 coefficients or model (4)-(6), contains 21 coefficient. But the number of coefficients can't serve as the sole indicator of the complexity of the model TF.

2. COMPLEXITY EVALUATION OF THE MODELS (4), (5)

In the work [2], the number of possible models of specified type of transformation functions is determined by the max possible degrees of pressure and temperature

$$N_M = \sum_{j=1}^{\max(K_P)} (\max([K_T]) + 1)^{j+1}, \quad (7)$$

where N_M - the number of possible models TF; K_P – degree of approximating polynomial respect to the parameter p; $[K_T]$ – set of degrees of approximating polynomials respect to the parameter t.

For example, if we assume: $\max(K_P) = 3, \max([K_T]) = 4$, then the number of possible models of TF will be 775. Complexity evaluation method of the models TF (4),(5) based [2] on the representation of each model, as the number that increases with increasing degree of parameters p и t.

Indicator of model complexity, which we call a number «D», formed as below. The number of digits of this number – N_D, determines by the max value KP , included in model: $N_D = \max(K_P) + 2$. For instance, for $\max(K_P) = 3, \max([K_T]) = 4$, rank of number «D» will be determined as following:

$$D = K_P K_{T3} K_{T2} K_{T1} K_{T0}. \quad (8)$$

Scale of notation of a number D is determined as a maximum value from a set of degrees. In this case, the base of scale of notation equals four.

However, the indicator of complexity cannot be used for all kinds of mathematical models (4)-(5). Using this indicator we can evaluate only those models, which were created sequentially incrementing the degree of pressure and temperature. For example, if $\max(K_P) = 2, \max([K_T]) = 1$, then by successive sorting we find, that the number of all possible models – 64, and using the method [2] we can estimate only 12 mathematical models.

3. NEW INDICATOR FOR COMPLEXITY EVALUATION OF THE MODELS (4), (6)

Total number of all the models created in the framework of expressions (4), (6) equal 220 = 1 048 576 (assume that the model FT always contains the coefficient β0). Total set of all the models in the amount of 1 048 576 can be partitioned into subsets containing models with the same number of coefficients (members).

Members included in the model are not equivalent. Graduation plan depends on the degree of the corresponding parameter (pressure or temperature) included in the mathematical model, and respectively depends the number of temperature points and pressure points.

Graduation plan should contain as less temperature points, as they determine the length [6] of the graduation, which reflects on its cost. Therefore, models, with the temperature parameter in the lowest degree, are more preferable.

Ranking members of the model (4), (6) in such way that priority has been given to the temperature exponent (table 1). The most significant are the members of the mathematical model with the greatest temperature exponent. Taking into account this method of ranking, define an indicator for the complexity evaluation of the models within one (each) subset

$$C = I \cdot (L \cdot Z) \quad (9)$$

where I=$[2^{20} 2^{19} \cdots 2^0]$ – column vector sized (1x21); allows make the switch from binary to decimal representation of the number «C»; L – matrix (table 2) sized (21x21); it is designed to go from the model of TF to binary number (binary representation of the indicator of complexity of the model) with a number of rank equal to 21. The first (lowest) rank of this number is equal to one, if the member β_0 is present in the model, otherwise - it equals zero; the second rank of this number is equal to one, if the member $\beta_6 t$ is present in the model, otherwise - it equals zero etc. for all members included to the model according to the table 1; Z – column vector sized (21x1). Vector consists of ones and zeros, correlated with the coefficients of evaluated TF model (one - when the corresponding coefficient is present in the model, zero - no) $\beta_0 \leftrightarrow z(1), \beta_1 \leftrightarrow z(2), \beta_2 \leftrightarrow z(3), \dots \beta_{20} \leftrightarrow z(21)$.

In the table 3 presented example of complexity evaluating of TF models, with the same number of coefficients (nine) and meet the requirements of reduced error.

The best models in this table are 4, 5 и 9, these models have the lowest indicators of complexity compare to the other models. In these models the temperature parameter is included in the second degree, and the pressure parameter in the third degree. This allows to use the graduation plan for three temperature points and four pressure points.

Table 1 – Ranking members of the models TF (4), (6)

Groups of the members of the model	Members of the models	Rank members of models	Weight members of models
Members of the model containing parameter: t	$\beta_5 t^5$	1	2^{20}
	$\beta_4 t^4$	2	2^{19}
Members of the model containing parameter: t и p	$\beta_{10} t^4 p$	3	2^{18}
Members of the model containing parameter: t	$\beta_3 t^3$	4	2^{17}
Members of the model containing parameters: t и p	$\beta_9 t^3 p$	5	2^{16}
	$\beta_{14} t^3 p^2$	6	2^{15}
Members of the model containing parameter: p	$\beta_{20} p^5$	7	2^{14}
	$\beta_{18} p^4$	8	2^{13}
Members of the model containing parameters: t и p	$\beta_{19} p^4 t$	9	2^{12}
Members of the model containing parameter: p	$\beta_{15} p^3$	10	2^{11}
Members of the model containing parameters: t и p	$\beta_{16} p^3 t$	11	2^{10}
	$\beta_{17} p^3 t^2$	12	2^{9}
Members of the model containing parameter: t	$\beta_2 t^2$	13	2^{8}
Members of the model containing parameters: t и p	$\beta_8 t^2 p$	14	2^{7}
	$\beta_{13} t^2 p^2$	15	2^{6}
Members of the model containing parameter: t	$\beta_1 t$	16	2^{5}
Members of the model containing parameters: t и p	$\beta_7 tp$	17	2^{4}
	$\beta_{12} tp^2$	18	2^{3}
Members of the model containing parameter:	$\beta_{11} p^2$	19	2^{2}
	$\beta_6 p$	20	2^{1}
Constant component of the model	β_0	21	2^{0}

Table 2 – Matrix L, sized (21×21)

	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}	β_{13}	β_{14}	β_{15}	β_{16}	β_{17}	β_{18}	β_{19}	β_{20}
β_5	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
β_4	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
β_{10}	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0
β_3	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
β_9	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0
β_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0
β_{20}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
β_{18}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0
β_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0
β_{15}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0
β_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0
β_{17}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0
β_2	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
β_8	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0
β_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0
β_1	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
β_7	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0
β_{12}	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0
β_{11}	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
β_6	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
β_0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3 – Example of evaluating the complexity of TF models with the same number of coefficients.

№	Indicator of complexity, binary (decimal) representation «	Type of models (number of coefficients equal 9)
1	000100000100010111111 (133 311)	$p^0(\beta_0+\beta_1 t+\beta_3 t^3)+p(\beta_6+\beta_7 t+\beta_8 t^2)+p^2(\beta_{11}+\beta_{12} t)+p^3\beta_{15}$
2	000000010110110100111 (11 687)	$p^0(\beta_0+\beta_1 t+\beta_2 t^2)+p(\beta_6+\beta_8 t^2)+p^2\beta_{11}+p^3(\beta_{15}+\beta_{16} t)+p^4\beta_{18}$
3	000001001101101000111 (19 879)	$p^0(\beta_0+\beta_1 t+\beta_2 t^2)+p(\beta_6+\beta_8 t^2)+p^2\beta_{11}+p^3(\beta_{15}+\beta_{16} t)+p^5\beta_{20}$
4	000000000110110110111 (3 511)	$p^0(\beta_0+\beta_1 t+\beta_2 t^2)+p(\beta_6+\beta_7 t+\beta_8 t^2)+p^2\beta_{11}+p^3(\beta_{15}+\beta_{16} t)$
5	000000000110111100111 (3 559)	$p^0(\beta_0+\beta_1 t+\beta_2 t^2)+p(\beta_6+\beta_8 t^2)+p^2(\beta_{11}+\beta_{13} t^2)+p^3(\beta_{15}+\beta_{16} t)$
6	000110000100000111111 (198 719)	$p^0(\beta_0+\beta_1 t+\beta_3 t^3)+p(\beta_6+\beta_7 t+\beta_9 t^3)+p^2(\beta_{11}+\beta_{12} t)+p^3\beta_{15}$
7	000110000110000110111 (199 735)	$p^0(\beta_0+\beta_1 t+\beta_3 t^3)+p(\beta_6+\beta_7 t+\beta_9 t^3)+p^2\beta_{11}+p^3(\beta_{15}+\beta_{16} t)$
8	000000001110110100111 (7 591)	$p^0(\beta_0+\beta_1 t+\beta_2 t^2)+p(\beta_6+\beta_8 t^2)+p^2\beta_{11}+p^3(\beta_{15}+\beta_{16} t)+p^4\beta_{19} t$
9	000000000111110100111 (4 007)	$p^0(\beta_0+\beta_1 t+\beta_2 t^2)+p(\beta_6+\beta_8 t^2)+p^2\beta_{11}+p^3(\beta_{15}+\beta_{16} t+\beta_{17} t^2)$

4. CONCLUSIONS

During this study were investigated two types of models of trans-formation functions. The model of the first type (4) and (5) is excrescent and expensive. Indicator of complexity [2] doesn't allow to reduce the plan of graduation, as operates with a limited number of TF models.

The second type of model (4)–(6) and an indicator (9) used for evaluation of its complexity; provide an opportunity to choose a simpler graduation plan. This allows to reduce the cost of pressure sensors tests, without impairment of their metrological characteristics [7].

REFERENCES

[1] Y.V. Udod, *Research and development of precision mathematical TF models and computational algorithms of the pressure values*, Taganrog, 2007. [Удод, Е.В. Исследование и разработка прецизионных математических моделей преобразования и алгоритмов вычисле-ний значений давления: автореф. дис. … канд. техн. наук / Е.В. Удод. – Таганрог, 2007.]

[2] N.A. Danilov, *Synthesis of transformation functions of measuring instruments for pressure control for a given limit of reduced error*, St. Petersburg, 2007. [Данилов, Н.А. Синтез функций преобра-зования измерительных приборов для контроля давления по заданному приделу приведенной погрешности: автореф. дис. … канд. техн. наук / Н.А. Данилов. – СПб., 2007.]

[3] V.V. Bychkov, *High-precision analog and digital pressure measuring transducers*, Tomsk, 2006. [Бычков, В.В. Высокоточные аналоговые и цифровые преобразователи давления: автореф. дис. … канд. техн. наук / В.В. Бычков. – Томск, 2006.]

[4] RMG 29-99 *GSI, Metrology. Key term*, Publishing house of standards, Moscow, 2000. [РМГ 29-99 ГСИ. Метрология. Основные термины. – М.: Изд-во стандартов, 2000. – 105 с.]

[5] A. L. Shestakov, A.P. Lapin, Y.A. Lapina, "The task of optimizing of transformation functions for measuring transducers", *Bulletin of The South Ural State University. Series* "*Computer Technologies, Automatic Control & Radioelectronics"*, nº, 2010. [Шестаков, А.Л. Задача оптимизации функций преобразования измерительных преобразователей/ А.Л. Шестаков, А.П. Лапин, Е.А. Лапина// Вестник ЮУрГУ, №2(178), серия «Компьютерные технологии, управление, радиоэлектро-ника». – 2010 – Вып. 11. – С.4 – 6.]

[6] GOST 22520 – 85, *Pressure sensors, rare-faction and differential pressure with electrical analog output signals GSP*, Publishing house of standards, Moscow, 1985. [ГОСТ 22520 – 85. Датчики давления, раз-режения и разности давлений с электри-ческими аналоговыми выходными сигна-лами ГСП. – М.: Изд-во стандартов, 1985. – 25 с.]

[7] Y.A. Lapina, *Algorithms of information processing for selecting and justification of transform function of pressure measuring transducers for process automation*, Chelyabinsk, 2011. [Лапина, Е.А. Алгоритмы обработки информации при выборе и обосновании функции преобразования измерительных преобразователей давления для АСУ ТП: автореф. дис. ... канд. техн. наук. – Челя-бинск, 2011.]