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A METHOD FOR THE NONLINEAR APPROXIMATION OF COMPLEX SHAPED CONVERSION FUNCTIONS

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Abstract. **The aim of the study** is to investigate the possibility of using the method and technique of piecewise nonlinear approximation for a highly accurate description (recognition) of the characteristics of the transformation of primary measuring devices (sensors), the transformation function (CF) of which has a rather complex form and a difficult to describe mathematical model. **Materials and methods.** The highly accurate description of this type of converter features provides for the division into nonlinear intervals over the entire measurement range. Each approximation interval forms a sequence falling between the extremum points of the considered CF and completely covers it. Besides, the third point between adjacent extremum points should be determined since it is the largest CF bending or turning point and allows expressing this approximation interval in the form of two different polynomials. Thus, each approximation interval is expressed in the form of two nonlinear functions – quadratic trinomials or cubic equations and is very close to the values of the real CF in this interval accurately describing the real CF. **Results.** The paper presents a developed hybrid test and structural measurement methods, as well as a relevant algorithm for implementting these measurement procedures. Test measurement methods use simple additive and multiplicative tests, as well as combinations of these tests – hybrid test measurements. Errors are automatically corrected or compensated to ensure high measurement accuracy. **Conclusion.** Unlike the known approximation methods, this approach accurately identifies the current states of the primary measuring instrument of the FP ensuring automatic calibration, and most effectively – the drift of the FP. Measurements at any time period are made relative to the value in which the sensor conversion feature is determined, which significantly improves measurement accuracy due to the intelligent information and measuring system based on structural and algorithmic-test measurement methods and its intelligent information support.

Keywords: measurements, improved accuracy, converter, conversion function, nonlinear approximation, test method

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МЕТОД НЕЛИНЕЙНОЙ АППРОКСИМАЦИИ ФУНКЦИЙ ПРЕОБРАЗОВАНИЯ СЛОЖНОЙ ФОРМЫ

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Аннотация. **Целью исследования** является изучение возможности применения метода и методики кусочно-нелинейной аппроксимации для высокоточного описания (распознавания) характеристик преобразования первичных измерительных приборов (датчиков), функция преобразования (ФП) которых имеет достаточно сложный вид и трудноописываемую математическую модель. **Материалы и методы.** Чтобы с высокой точностью описывать такой тип характеристик преобразователя, надо разбить на нелинейные интервалы весь диапазон измерений. Каждый интервал аппроксимации образует последовательность, располагаясь между точками экстремума рассматриваемой ФП, и полностью покрывает его. Также важно определить третью точку между соседними точками экстремума, потому что эта точка является самой большой точкой изгиба или поворота ФХ и позволяет выразить этот интервал аппроксимации в виде двух полиномов, отличающихся друг от друга. Таким образом, каждый интервал аппроксимации выражается в виде двух нелинейных функций – квадратных трехчленов или кубических уравнений – и очень близок к значениям реального ФП в этом интервале, описывая реальный ФП с большой точностью. **Результаты.** Для реализации вышеизложенного созданы гибридные тестовые и структурные методы измерений, а также соответствующий алгоритм реализации этих процедур измерений. При тестовых методах измерения используются простые аддитивные, мультипликативные и комбинации этих тестов – гибридные тестовые измерения, автоматически исправляются или автокомпенсируются погрешности и обеспечивается высокая точность измерений. **Заключение.** В отличие от известных методов аппроксимации, при таком подходе с высокой точностью идентифицируются текущие состояния первичного средства измерения (прибора) ФП, производится автоматическая калибровка, а самое эффективное – дрейф (перемещение) ФП. Поскольку измерения, выполняемые в любой момент времени, производятся относительно ситуации (значения), в которой определяется характеристика преобразования датчика, в результате точность измерения существенно увеличивается. Все это возможно благодаря интеллектуальной информационно-измерительной системе, построенной на основе структурных и алгоритмически-тестовых методов измерения, и ее интеллектуальному информационному обеспечению.

Ключевые слова: измерения, повышение точности, преобразователь, функция преобразования, нелинейная аппроксимация, тестовый метод

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Introduction

High-quality production becomes a reality due to the complex automation of production processes (PP) and will depend on the class of the tailored automated information-measuring and control system, as well as the reliability and accuracy of the useful information obtained through the use of this system [1–4].

Priority is given to information and communication technologies (ICT), as well as high tech-based advanced automation elements and devices. Their complex integration and well-thought-out architecture ensure high efficiency [5, 6].

Conversion functions (CF) of measuring systems are nonlinear in reality, and this feature increases even more in operating conditions. Measurement errors occur in real measurements since the defined mathematical model of conversion features differs from its initial state, and the identification of conversion features becomes relevant. Many studies have covered this field and deeloped appropriate theoretical and practical methods [7–9].

High measurement accuracy of modern measuring systems can be achieved through the implementation of intelligent measurement procedures as opposed to classical methods, which can be highly effective. Numerous studies have been carried out and algorithmic test methods developed on the basis of our information-measuring systems (IMS) in real operating conditions have been successfully applied to improve measurement results [10].

Intelligent IMSs imply the introduction of intelligent electronic modules into the system structure [1]. The article proposes a different approach to test the process in the IMS in such a way as to obtain high measurement accuracy. The identification and evaluation of the results obtained through the use of nonlinear approximation are discussed below.

The measurement accuracy of the primary measuring system with nonlinear conversion features is improved due to structural and information redundancy and the selection of optimal tests, construction and solution of test equations [10].

1. Problem statement

In real operating conditions, the conversion functions (CF) of primary measuring instruments are complex and continuous. In many cases, the mathematical model (MM) of the conversion functions of the initial measuring system is set in the following polynomial form [10]:

$$y = \sum_{i=0}^{n} a_i x^{i-1}. \qquad (1)$$

The instability of the a_i parameters of the conversion function is known to reduce measurement accuracy. It was proposed to design IMSs based on the test measurement method to eliminate this effect. In equation (1), a_i are the coefficients of the conversion function, $i = \overline{0, \ldots, n}$ assumes that the measurement operation is performed by adding n tests or n degrees of a polynomial [10].

Since they cannot be described mathematically, they should be approximated by a description in the form of piecewise nonlinear polynomials over the entire measurement range.

Each approximation range may be expressed by the lowest possible degree – quadratic or cubic polynomials for high measurement accuracy, without exceeding the measurement error of the set limit and operation simplicity.

2. Problem solution

Let us assume that the results of the measurement operation performed in a certain range consist of the following nonlinear graph (Fig. 1). The curve connecting the two extremum points inside each circle is described by a mathematical expression and can be obtained as a separate nonlinear function.

One of the main criteria for the test set optimality used to identify the nonlinear conversion functions of primary measuring systems is the minimum degree of the basic test equations (BTE) obtained during its implementation, as well as the minimum measurement error.

Below, we consider the nonlinear approximation of conversion functions and study the measurement error using the measurement method testing.

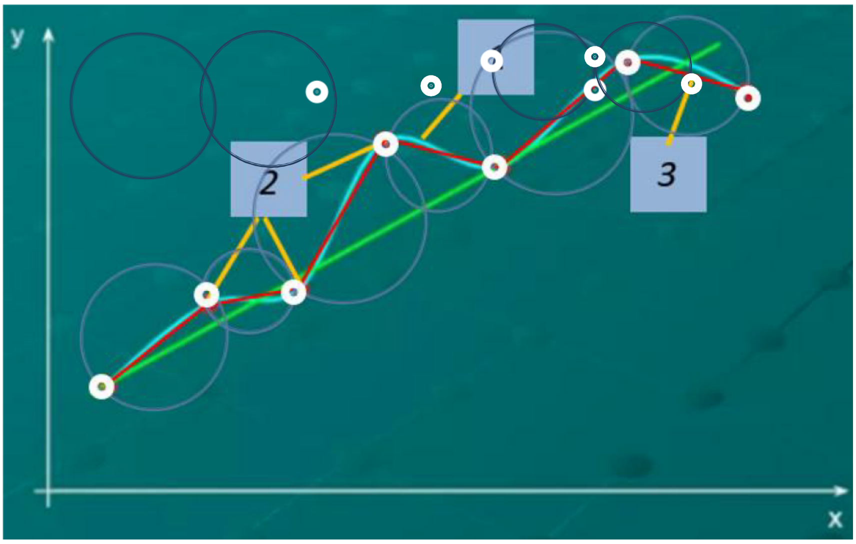

Fig. 1. Nonlinear approximation of complex shaped conversion functions: 1 is the conversion function (light blue); 2 is the extreme points of the conversion function (white); 3 is the piecewise linear approximation of the conversion function (red)

A comparative check of successive models competing with each other is carried out based on the F-criterion to make a better choice [11]:

$$F(m-n),\left[m-(n+1)\right]=\frac{\delta^2_{y_{n-1}}}{\delta^2_{y_n}}. \qquad (2)$$

In this case, we check the assumption that the n-th order regression model describes the desired function value better than the $n-1$ order regression model. According to the formula, the obtained table values based on the *F*-criterion are selected by their significance level and compared with each other. If the value is higher than the corresponding table value, the assumption is accepted. In other words, a conclusion is made that it is advisable to use the n-level model, rather than $n-1$. Thus, all competing models can be sequentially tested.

The results of numerous tests show that, according to the description of the method for selecting a mathematical model of an approximating curve in the aforementioned conditions, the degree of the cubic or quadratic polynomial is taken to be equal to three, and the mathematical model of the dependence of the relative error on the measurement value will be described as follows [10]:

$$\delta = a_0 + a_1\Delta x + a_2\Delta x^2 + a_3\Delta x^3, \qquad (3)$$

wherein the measuring system error is reduced to Δx, not exceeding the permissible standard deviation limit.

Unlike the structural-algorithmic method, the use of θ additive, k multiplicative, and $\theta\cdot k$ hybrid tests as comparison standards in the measurement operation instead of a_0, a_1, a_2 and a_3 is predetermined by the accuracy of these tests.

Thus, the highly accurate identification of the curves of primary measuring system conversion functions is determined by the mathematical model of two curves between the extremum points of the conversion functions.

According to numerous studies, the use of the conversion functions of primary transmitters in the form of quadratic trinomials significantly simplifies approximation and reduces the number of measurement cycles. This method is considered to be more effective than the known methods [11–15].

Let us consider the following quadratic trinomial taken as an approximating curve:

$$y_0 = a_0 + a_1 x + a_2 x^2. \qquad (4)$$

The x measurement value in the equation is input in a special algorithmic sequence to the primary measuring systems simultaneously with the additive ($x+\theta$), multiplicative (kx) and mixed ($kx+\theta$) tests, while the basic test equations (BTE) are as follows:

$$\begin{cases} y_0 = a_0 + a_1 x + a_2 x^2; \\ y_1 = a_0 + a_1(x+\theta) + a_2(x+\theta)^2; \\ y_2 = a_0 + a_1(kx) + a_2(kx)^2; \\ y_3 = a_0 + a_1(kx+\theta) + a_2(kx+\theta)^2, \end{cases} \quad (5)$$

where a_0, a_1, a_2 – the primary conversion feature measuring systems – are the nominal values of the quadratic trinomial coefficient in the relevant approximation ranges.

3. Device operating principle and error algorithm

Test equations (5) are implemented through the following device (Fig. 2):

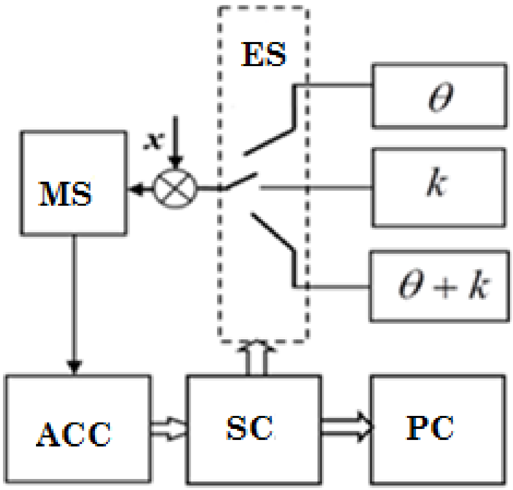

Fig. 2. Structural diagram of the measuring device: MS is the measuring system (converter); ACC is the analog-to-code converter, ES is the electronic switch; SC is the softcontroller, PC is the personal computer

The electronic switch (ES) alternately connects and disconnects the standards to the input of the measuring systems (MS) according to the measurement algorithm – BTE (5), and the measured x value is always connected to the input of the measuring systems and measured simultaneously with the standards – tests: ($x+\theta$), (kx), and ($kx+\theta$). The results of all three measurement cycles are converted into a code via the analog-to-code converter (ACC) and transmitted to the softcontroller (PSC), processed on the PC, and finally, a conversion function (CF) is obtained by solving the BTE on the PC:

$$y_0 = \frac{\left[x(k-1)+\theta\right](y_1 - y_2) + \left[x(k-1)-\theta\right]y_3}{x(k-1)-\theta}. \quad (6)$$

The following expression is obtained based on the measurement results from (6) for calculating the measured value:

$$x_{cal} = \frac{(y_1 - y_2) + (y_0 - y_3)}{(y_0 - y_3) - (y_1 - y_2)} \cdot \frac{\theta}{k-1}. \quad (7)$$

The absolute error of the tested measuring systems will be determined by the following expression:

$$\Delta_T = [x(k-1)+\theta](\Delta_1 - \Delta_2) + [x(k-1)-\theta](\Delta_3 - \Delta_0). \quad (8)$$

If we take into account that the relative error of the test measuring system is determined by expression (8) and the value of the absolute error created by additive and multiplicative tests in each measurement cycle (MC) is replaceable, we can obtain the following expression for the error components generated in all cycles:

$$\Delta_T = \theta\left[\Delta_1 - \Delta_2 - (\Delta_3 - \Delta_0)\right] + x(k-1)\cdot\left[\Delta_1 - \Delta_2 + (\Delta_3 - \Delta_0)\right]. \quad (9)$$

The following expression is obtained for the absolute error Δ_{in} input to the tested measuring system:

$$\Delta_{in} = \frac{\Delta_T}{f_T'(x)}. \tag{10}$$

Here

$$f_T(x) = (y_0 - y_3)[x(k-1) - \theta] + (y_2 - y_1)[x(k-1) + \theta]. \tag{11}$$

Upon differentiation of $f_T'(x)$, the following expression is obtained:

$$f_T'(x) = (k-1)\left[(y_0 - y_3) - (y_1 - y_2)\right]. \tag{12}$$

Taking into account expressions (10), (9), and (11), the following expression is obtained for the absolute error input to the tested measuring system:

$$\Delta_{in} = \frac{\left\{\theta\left[(\Delta_1 - \Delta_2) - (\Delta_3 - \Delta_0)\right] + x(k-1)\left[\Delta_1 - \Delta_2 + (\Delta_3 - \Delta_0)\right]\right\}}{(1-k)2\theta\left\{b_1 + b_2\left[(k-1)x + \theta\right]\right\}}. \tag{13}$$

Thus, the following expression is obtained for the variance of the absolute error of the tested measuring systems independent of each other:

$$\sigma_{\Delta T}^2 = \sigma_{\Delta_0}^2 [z - \theta]^2 + \theta_{\Delta_1}^2 [z + \theta]^2 + \sigma_{\Delta_2}^2 [z + \theta]^2 + \sigma_{\Delta_3}^2 [z - \theta]^2, \tag{14}$$

where $\sigma_{\Delta i}$ is the measurement cycle of the corresponding standard deviation error.

As a result, we obtain the following formula for the absolute error input to the initial measuring system:

$$\Delta_{in \cdot T} = \frac{\Delta_M}{k-1} - \frac{\Delta_\theta}{\theta}. \tag{15}$$

An important conclusion from expression (15) is that the components of the final error of the test measuring system $\Delta_{in \cdot T}$ operating on the basis of the measurement algorithm (6) do not depend on the coefficients of the measuring system conversion function when implementing the optimal test set.

Errors Δ_θ and Δ_M are generally not intercorrelated, they are continuous random variables and obey the normal distribution law. Consequently, the relative error ($\delta_{in \cdot T}$) input to the test measuring system, in turn, is a continuous random variable characterized by the mathematical expectation (M_{δ_T}) and the variance ($\sigma_{\delta_T}^2$).

The mathematical expectation is determined by the following expression:

$$M_{\delta_T} = \frac{M[\Delta_M]}{k-1} - \frac{M[\Delta_\theta]}{\theta}, \tag{16}$$

where Δ_M and Δ_θ are the mathematical expectations of the random variables $M[\Delta_M]$ and $M[\Delta_\theta]$, respectively.

The variance $\sigma_{\delta_T}^2$ is determined by the following formula:

$$\sigma_{\delta_T}^2 = \frac{\sigma_{\Delta_M}^2}{(k-1)^2} + \frac{\sigma_{\Delta_\theta}^2}{\theta^2}, \tag{17}$$

where Δ_M and Δ_θ are the standard deviations of the random variables σ_{Δ_M} and σ_{Δ_θ} respectively.

Thus, when comparing the calculated values of the variances $\sigma_{[\delta_T]}^2$ and $\sigma_{[\delta_T^*]}^2$, it becomes clear that the resulting error components created in the test measuring system, implemented with the optimal combinations of additive, multiplicative, and hybrid tests with a variance, are less than the error in similar test measuring systems implemented through the use of simple additive and multiplicative tests. No additional time is needed when the test measuring system has quadratic-trinomial conversion features and solves basic test equations [10].

For instance, if we take a test set of x, $x+\theta_1$, $x+\theta_2$, the kx test for the full measurement cycle of the test measuring system will have output values according to $y_0, \ldots, y_3$, and the following basic test equations will be obtained:

$$\begin{cases} y_0 = b_0 + b_1 x + b_2 x^2; \\ y_1 = b_0 + b_1(x+\theta_1) + b_2(x+\theta_1)^2; \\ y_2 = b_0 + b_1(x+\theta_2) + b_2(x+\theta_2)^2; \\ y_3 = b_0 + b_1 kx + b_2(kx)^2. \end{cases} \tag{18}$$

If we take into account the errors caused by inaccurate measurement cycles of the tested measuring system, we obtain the following expressions:

$$\begin{aligned} &\Delta_{T1} = \left[b_2 + 2b_3(x+\theta_1)\right]\cdot\Delta_{\theta_1}; \\ &\Delta_{T2} = \left[b_2 + 2b_3(x+\theta_2)\right]\cdot\Delta_{\theta_2}; \\ &\Delta_{T3} = \left[b_2 + 2b_3 kx\right]\cdot\Delta_M \cdot x. \end{aligned} \tag{19}$$

If the conversion feature of the test measuring system is presented in the form of the $n=3$ degree polynomials, we obtain the following expression when writing the main test in the initial equations and solutions of the measuring system conversion:

$$y_0 = \frac{y_1 x(k-1)\theta_2\left[x(k-1)-\theta_2\right] - y_2 x(k-1)\theta_1\left[x(k-1)-\theta_1\right] + y_3\theta_2\theta_1(\theta_2-\theta_1)}{\left[x(k-1)-\theta_1\right]\left[x(k-1)-\theta_2\right](\theta_2-\theta_1)}. \tag{20}$$

Thus, we obtain the following expression from expressions (19) and (20) for the absolute error of the test measuring system:

$$\begin{aligned} \Delta_T^* = {} & x(k-1)\theta_2\left[b_2 + 2b_3(x+\theta_1)\right]\left[x(k-1)-\theta_2\right]\Delta_{\theta_1} - \\ & - x(k-1)\theta_1\left[b_2 + 2b_3(x+\theta_2)\right]\left[x(k-1)-\theta_1\right]\Delta_{\theta_2} + \\ & + x\left[b_2 + 2b_3 kx)\right]\theta_2\theta_1(\theta_2-\theta_1)\Delta_M. \end{aligned} \tag{21}$$

According to expression (19), we obtain the following expression for the relative error input to the test measuring system:

$$\delta_{in}^* = \frac{\left[x(k-1)-\theta_2\right]\left[b_2 + 2b_3(x+\theta_1)\right]}{(b_2 + 2b_3 kx)(\theta_1-\theta_2)}\cdot\frac{\Delta_{\theta_1}}{\theta_1} - \frac{\left[x(k-1)-\theta_1\right]\left[b_2 + 2b_3(x+\theta_2)\right]}{(b_2 + 2b_3 kx)(\theta_1-\theta_2)}\cdot\frac{\Delta_{\theta_2}}{\theta_2} + \frac{\Delta_M}{k-1}. \tag{22}$$

We obtain the following expressions for the mathematical expectation and variance of the relative error of the test measuring system:

$$\begin{aligned} & M_{\left[\delta_{in}^*\right]} = 0; \\ & \sigma^2_{\left[\delta_{in}^*\right]} = \frac{\left[x(k-1)-\theta_2\right]^2\left[b_2 + 2b_3(x+\theta_1)\right]^2}{(b_2 + 2b_3 kx)^2(\theta_1-\theta_2)^2}\cdot\frac{\delta^2_{\Delta_{\theta_1}}}{\theta_1^2} + \\ & + \frac{\left[x(k-1)-\theta_1\right]^2\left[b_2 + 2b_3(x+\theta_2)\right]^2}{(b_2 + 2b_3 kx)^2(\theta_1-\theta_2)^2}\cdot\frac{\delta^2_{\Delta_{\theta_1}}}{\theta_2^2} + \frac{\delta^2_{\Delta_{\theta_1}}}{(k-1)^2}. \end{aligned} \tag{23}$$

Conclusion

Expressions (17) and (23) show that the accuracy of the value using the multiplicative tests and weighting coefficients of other components are equal in magnitude, and the measuring system does not depend on the parameters of conversion functions. When additive tests are used, their accuracy does not coincide, while weighting coefficients are qualitatively different. These two expressions demonstrate that even if the weighting coefficient in the first expression is equal to one, the coefficients in the second expression depend on the parameters of the conversion functions of the system measurements and the relationships between the values of additive and multiplicative tests. Thus, the aforesaid proves the advantage of the measurement method, when implementing both tests and their optimal set.

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