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Mathematical Modeling of the Digital Measuring Signal of Intelligent Flowmeters

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Abstract. The research contains theoretical analysis of the possibilities of development of a new type of devices for measurement of the consumption of energy resources in the communal services system. Novel alternatives for improvement of intelligent measuring instruments are offered in the article. On the basis of the presented calculation method, a mathematical model of the digital measuring signal for intelligent flowmeters at a uniform and at a non-uniform flow of liquids is offered. This would allow increasing the accuracy of the measuring signal as well as creating a new type of intelligent measuring devices for exact accounting of the consumption of energy resources in separate households of the communal services system. Theoretical researches showed that traditional flowmeters of cold and hot water in separate premises are unsuitable for commercial calculations as they make measurements in the critical zone of the error of the device, thus exceeding the admissible accuracy standard norm. Therefore the present state standards of Latvia for the water and heat energy account in households should be reconsidered. For assessment of the parameters of flowmeter's target signal, a calculation method of the mathematical model with two keys of digital signals (basic and automatic correction) is offered. The main reasons of fundamental errors are defined. Examples how to calculate the target measuring signal are given. By using Laplace transform method, a novel mathematical calculation model of the measuring and correction signals of intellectual flowmeters has been developed.
Key words: Modeling, intelligent sensor, measurement, error correction.

Introduction

Technological revolution in all the production spheres, especially in the computing- and research-comprising technology branches, has determined the application of local (divided intellect) systems in the functioning structures as well as the further development of intelligent sensors. Sensors are the front end devices for information acquisition from the natural and artificial world. Recent advances in the technology of sensors and actuators have much contributed to the fulfilment of these demands. Many modern systems and products are now equipped with electronic sensors and actuators, resulting in sophisticated functionality and novel applications (Moskvins, 1996; Regtien, 2005). The intelligent sensor consists of a primary sensing element supported by specific algorithms and associated electronic data sheets. The main elements of intelligent sensors are the primary sensing element, excitation control, amplification, analogue filtering, data conversion, errors compensation, and digital information and digital communication processing (Yamasaki, 1996).

In order to increase accuracy of measurements and to save energy and other expensive resources, it is necessary to investigate new possibilities connected with application of information technologies, expert systems, and systems of artificial intelligence. Just in such a way can be explained the world tendency towards *intellectualization* of measuring devices and sensors (Moskvin, 1998; Moskvins, 1996; Moskvin, Spakovica, 2005). Therefore elaboration of intelligent sensors becomes the main direction in the development of intelligent measurement systems.

The intelligent sensors can essentially perfect the whole control system because of the increase in preciseness and rational processing of signals received from the sensory element (Yamasaki, 1996). Fundamental research in the field of application of intelligent sensors for saving of energy and other resources allows creating abstract universal models which *improve* the real processes, and, in the result, the investigated situation becomes transparent, accessible to theoretical analysis, generalizations and for the defining of new knowledge. Intelligence

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of any type of sensors refers to any object in such a way as it is required by its nature (Moskvins, 1996; Moskvin, 1998).

The complex set of intelligent household flowmeters "Logicor" includes devices for measurement of the consumption of cold and hot water, of thermal and electric energy, as well as of gas in the automated technological processes and in the households of the communal services system. The high-technology "Logicor" methods contain programs of metrological certification and accuracy estimation, including algorithms of error correction, communication interfaces of electric devices and radio systems, special interface for automatic data accumulation, and accuracy analysis (Moskvins, Spakovica, Moskvins, & Shahtarina, 2012).

The method and intelligent measuring device "Logicor" allow providing preliminary mathematical, physical and metrological modeling of the measurement process at the place of measurement, i.e. in real household conditions. This guarantees more exact and authentic results of measurements and allows providing faultless accounting of the consumed energy resources. Besides the applied optimized programs, algorithms, know-how, processors, effective radio-frequency devices, the full set of components for the system of intellectual measurements of the quantity of water, heat, and gas, as well as of the consumed electricity is provided.

Usually, in the elaboration of intelligent sensors, the traditional methodological approach does not provide a sufficiently complete idea about all inner processes going on in the object under exploration, because functional structure of the synthesized device is fully oriented only towards realization of the in-advance programmed functions (Moskvin, 1998).

Subsequently, it can be assumed that registering co-operation results of the investigation object with different measuring devices, the object's properties, which have to be fixed, can be so significantly different that there can be no essence at all in the indications of the measuring device, because exploration of the object is always connected with a definite *space–time* co-ordinate system (Moskvin, Spakovica, 2005). In the currently used flowmeters, the accounting system of energy resources under small-amount consumption regime causes the measurement error of up to 10–25 percent (Moskvins, 1996). Such error exceeds the admissible norms.

Therefore, the purpose, scope and novelty of our investigation is connected with a new notion *intelligent sensors* and with a novel approach in the modeling of the digital measuring signal for intelligent flowmeters, which allows creating an exact accounting system of energy resources in separate households of the communal services system.

Methods and Materials

The research objects are: target signal of intelligent flowmeters in the mode of correction of measurement error; primary measuring transducers for measurement of the cold and hot water and of the heating and electric energy; mathematical, physical and metrological models; programs and algorithms of intelligent (teaching, self-diagnostics) and metrological ensuring (evaluation, control of the preciseness of the measuring result, and correction of errors).

The following main versions of the measurement of water meters were taken. The "Logicor" can be integrated into the control and regulation systems and can be retrofitted in the mechanical meter, making installation easier. The basic measurement device system functions as a dry running-water meter with a mechanical roll meter. The contact-free and non-wearing scan records the flow amount for the mechanical meter and saves it in the radio module. The consumed amount is then transmitted with further meter-relevant data by radio transmission on the reference date, which allows reading the meter without having to enter the flat. The version of the meter with an integrated modulator plate makes it possible to retrofit it with a radio module (GPRS*) for wireless data transmission of the consumption data. The flow rate is recorded with a contact-free and magnet-free sensory mechanism.

The quantity of the volume of the testable liquid on the reference date, flow rate, and consumption are fixed by means of a light-emitting diodes display. The integrated interface enables connection to M-Bus (Meter-Bus) systems for cable-dependent remote transmission. M-Bus is a European standard (EN 13757-2 physical and link layer, EN 13757-3 application layer) for remote reading of gas or electricity meters. M-Bus is usable also for other types of consumption meters. The radio variant of M-Bus (wireless M-Bus) is specified in EN 13757-4. Control of modeling results was carried out using methods described in detail in relevant USA and European patents (Moskvin, 1991a, b, c; 1993a, b, c, d, e).

* General packet radio service (GPRS) is a packet-oriented mobile data service on cellular communication system's global system for mobile communications (GSM).

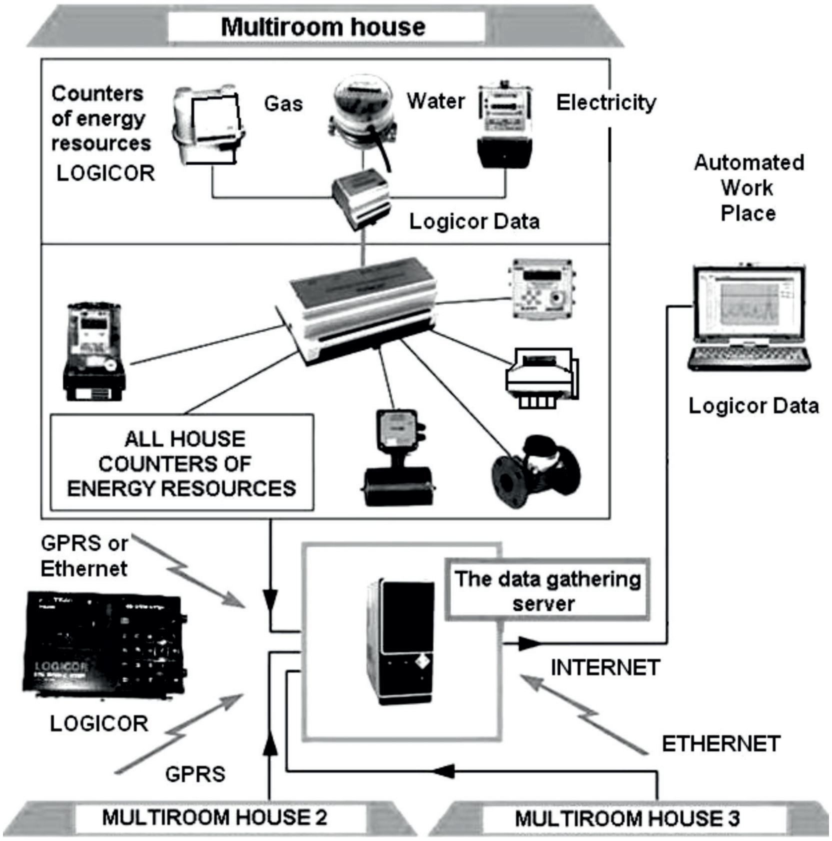

Fig. 1. The generalized scheme of control system "Logicor" for accounting of energy resources consumption in households and apartments of the communal services system.

The "Logicor" intelligent measurement system is applicable as a calibration device in separate households in the communal services system. The "Logicor" flowmeter has an electronic measuring device that allows wireless data transmission using a radio module. The appropriate components are available for all installation situations. As no wiring at all is required, there is no need for structural work. All consumption data is recorded by a mobile receiver outside the home and is transmitted remotely to the "Logicor" data centre (Fig. 1).

On the programmed reference date, which is freely selectable, the device saves the consumption amount and sets the current display. Disturbance messages are effected automatically, and the user is notified of them on the display; if radio operation is used, the messages are conveyed to the meter reader via radiogram. In the "Logicor" intelligent measurement system, all devices equipped with radio technology can be metrologically checked on the place, and potential sources of measurement errors can be rectified on the place using the algorithm of correction (Moskvin, 2003). All the methods of measurements, design of experimental devices, as well as know-how of calibration are internationally patented (Moskvin, 1991a, b, c; 1992; 1993a, b, c, d, e).

Our theoretical research shows that traditional flowmeters of cold and hot water in separate premises are unsuitable for commercial calculations as they make measurements in the critical zone of the error of the device thus exceeding the admissible accuracy standard norm (Moskvins, Spakovica, Moskvins, & Shakhtarina, 2012). According to Kotelnikov's theorem, binary intelligent sensors applied in the digital control system are more preferable than the analog type of sensors. Our analytical research was focused on the elaboration of mathematical models of digital intelligent measuring systems.

The research method for elaboration of intelligent accounting system meets the requirements of the European Council Directive 2004/22/EC (Annexes 1 and MI-004) on measurement instruments, EC Directive 2006/95/EC, harmonized standards under Directive 1999/5/EC, harmonized European standard EN 1434 (2007), Directive 71/319/EEC (meters for liquids other than water), Directive No 617/2010 concerning notification to the Commission of investment projects in energy infrastructure within the European Union, Directive 2004/17/EC of the European Parliament and of the Council of 31 March 2004 coordinating the procurement procedures of entities operating in the water, energy, transport and postal services sectors, Directive No. 1083/2006 (16 June 2010) (EU, Euratom), and Directive No. 833/2010 implementing Council Regulation (EU, Euratom).

The basic results were received and formed in a complete agreement with the existing notions, data of modeling, and level of knowledge about the investigation process and objects with the trend being towards the convergence of development of intelligent technology in order to estimate the factors affecting the error and the level of preciseness of sensors for saving the material resources and energy (Moskvin, 2003).

Results and Discussion

The main tasks of the research were: theoretical researches of metrological ensuring of the measurement channel, and substantiation of the calculation method of target signal in the real-time mode of correction of the error of intelligent flowmeters. The new type of intelligent home flowmeter "Logicor" includes devices and know-how for calibration and measurement of the consumption of cold and hot water, of thermal and electric energy, as well as of gas in separate households of the communal services system (Fig. 1).

Presence of the peculiarities of specific technological processes has caused creation of such models of measuring systems which at a higher rate would correspond to perspective tasks and aims both of artificial intelligence systems and of the fundamental problems of accuracy.

The novel approach in modeling intelligent measurement systems allows examining two types of models. For elaboration of the first type of models, it is sufficient to study in isolation only inner parameters and processes of the object under exploration without taking into consideration the impact of outer medium factors and, in relation with it, behaviour changes of the structure intended for synthesis. Further use of the model depends only on the success of the theoretical and technical development of an idea.

For elaboration of the second type of models, the measuring system with an intelligent sensor should be considered, which by means of calculation device in the further steps of the modeling allows using the basic and additional signals for the correction of the measurement errors. Further, the reference function and feedback algorithm in the form of self-learning programs can be determined.

The results of analysis of modern traditional and untraditional–statistical methods as well as of the evaluation methods of measurement results, and the main reasons of fundamental errors are pointed out. This allows excluding the main energy and water measurement errors.

In connection with transition from the systems of general accounting of the consumption of water and heat in certain buildings of the communal services system to accounting of water and heat in separate households and apartments, it is obvious that the volume of measurements of the consumed energy resources is insufficient for making measurements with the necessary accuracy. This leads to the conflicts between producers and consumers of heat and water resources in the course of their accounting and to considerable losses of heat energy and of cold and hot water in separate households.

According to the EC Directives, home flowmeters should meet the following requirements: easily and quickly assembled, comfortable radio modules, high precision measurement. In the EU, traditional flowmeters have such performance features: stability due to use of the multi-jet axial principle, dry running water meter with a pivotal roll meter, for cold water up to 30 °C or for hot water up to 90 °C, design approval and calibration included, easy to install and flexible due to the measuring capsule principle, suitable for flush, surface and valve meter installation.

However, in the Baltic States, houses designed in the Soviet times do not allow using the advantage of intelligent measuring systems. This is the reason why the measuring devices that the EU recommends for application in the old-style apartments and houses function extremely inaccurately. Losses due to inexact measurement of energy resources make, for example, in Latvia, 25 and more percent (Moskvins, Spakovica, Moskvins, & Shahtarina, 2012). Therefore, at the Latvia University of Agriculture, retrofitting of the flowmeter for new and old inhabited buildings was carried out by means of the intelligent measurement system.

For determination and assessment of the parameters of flowmeter's target signal, a mathematical calculation model with two keys of digital signals (basic and correction) was elaborated. This allowed increasing the accuracy

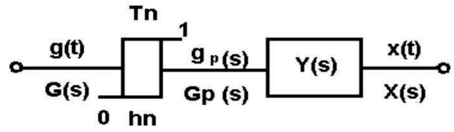

Fig. 2. The block scheme for calculation of the measuring signal at a uniform stream of liquid

of measurements by use of standard devices under specific conditions of the old-design houses.

It is possible to present the correction signal as a mathematical model of the measuring device in the form of a block scheme (Fig. 2). We presented the correction signal of the measuring device in the form of a digital filter that creates a digital impulse signal with modulation of the second type affects. To define reaction of the measuring system, it is necessary to define *p* transformation of the entrance signal in the form of $G_p(s)$, and then – to calculate the Laplace transform for the target signal using the following formula (Kuzin, 1962; Chernikh, 2008):

$$X(s) = G_P(s)Y(s). \qquad (1)$$

Using special tables, it is possible to choose a standard-type signal of the working flowmeter as a time function at a uniform stream of liquid:

$$G(s) = 1/s, \qquad (2)$$

$$Y(s) = 1/(s+a), \qquad (3)$$

where α – a factor of smoothing of a signal.

It is also possible to define reaction of the system's target signal as a result of *p* transformation of the entrance signal:

$$G_P(s) = P_{h,T}(1/s), \qquad (4)$$

where *h* and *T* – indexes of time of an electronic key in the condition *on* and *off*.

From the last formula, according to the rules of *p* transformation, an equation is obtained:

$$G_P(s) = \frac{1-e^{-hs}}{s(1-e^{-Ts})}. \qquad (5)$$

From formula (1), an equation of Laplace transform for the target signal is obtained:

$$X(s) = G_P(s)Y(s) = \frac{1-e^{-hs}}{(1-e^{-Ts})}\frac{1}{s(s+a)}. \qquad (6)$$

From equation (6), target signal can be defined as the sum of two shifted functions:

$$L^{-1}\{\frac{1-e^{-hs}}{s(s+a)}\}, \qquad (7)$$

where the interval of shift is equal to 0, t, 2t and so on. It corresponds to the following ratio:

$$\frac{1}{(1-e^{-sT})} = 1 + e^{-sT} + e^{-2sT} + ... + e^{-nsT}. \qquad (8)$$

The original of function X(s) is defined directly from the Laplace transform tables:

$$X(t) = [1-d(-h)\{\frac{i}{\alpha} - \frac{1}{\alpha(e^{\alpha T}-1)}[e^{\alpha\sigma T} - e^{-\alpha T}]\}, \qquad (9)$$

where *d(–h)* specifies the time delay.

Formula (9) allows calculating the correction signal of the intelligent measuring device at any time moment *T*.

Considering that

$$t = iT + \sigma T, i = 0,1,2,3...,0 < \sigma < 1$$

at numerical values *α*=1, T=0.5, the final equation of the digital correction signal can be defined as follows:

$$X(t) = [1-d(-h)]\{0{,}5i \frac{1}{e^{0{,}5\sigma}-1}[e^{0{,}5\sigma} - e^{-T}]\}. \qquad (11)$$

An example how to calculate the target signal using two electric keys is shown in Fig. 3. In case of a non-uniform flow of liquid, the actual discrete correction signal can be calculated by the Laplace *p* transformation method using two electric keys (Kuzin, 1962):

$$X(s) = \frac{1}{1-e^{-ksT_1}} X_0(s), \qquad (12)$$

where *k* – a whole positive number;
$X_0(s)$ – function that corresponds to the Laplace transform for signal X_0 corresponding to $X(t)$ in the interval $0<t<kT_1$.

Further, we assumed that two periods T_1 and T_2 of electronic key are connected by the ratio

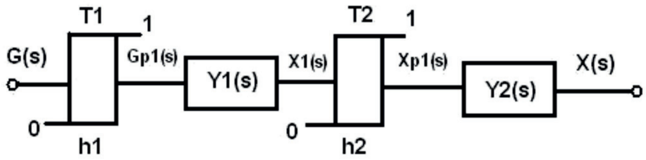

Fig. 3. The block scheme for calculation of the measuring signal at a non-uniform stream of liquid.

$$\frac{T_1}{T_2} = \frac{b}{q}, \tag{13}$$

where b and q – whole positive numbers.

The Laplace transform for the target signal can be defined by the formula:

$$X(s) = Y(s) G_n(s). \tag{14}$$

The original of the tested signal can be defined using tables of the Laplace p transform.

We assumed that the standard signal form according to the block scheme in Fig. 3 is:

$$G(s) = \frac{1}{s} \tag{15}$$

and

$$Y_1(s) = \frac{1}{s+1}. \tag{16}$$

For example, from data of the experiment on a real physical model, preliminary parameters of two real signals were obtained:

$$h_1 = 0.6s; T_1 = 1s; h_2 = 0.2s; T_2 = 0.4s.$$

The target signal from the first electronic key can be defined using tables of the Laplace p transform:

$$Gp_1(s) = \frac{1-e^{-sh_1}}{1-e^{-sT_1}}\left[\frac{1}{s}\right]. \tag{17}$$

Therefore, entrance signal for the second key conforms to the following equation:

$$X_1(s) = \frac{1-e^{-sh_1}}{1-e^{-sT_1}}\left[\frac{1}{s(s+1)}\right]. \tag{18}$$

As the second electronic key works during time period T_2, the relation for this time period can be transformed as:

$$\frac{T_1}{T_2} = \frac{5}{2}; b = 5; q = 2. \tag{19}$$

Using formula (18), equation (19) can be rewritten in the form:

$$X_1(s) = \frac{(1-e^{-sh_1})(1-e^{-\frac{5}{2}sT_2})}{1-e^{-\frac{5}{2}sT_2}}\left[\frac{1}{s(s+1)}\right]. \tag{20}$$

Using tables of p transformation, an equation is obtained:

$$X_{p1}(s) = \frac{1}{1-e^{-5sT_2}}(1-e^{-2sT_2}-e^{-3sT_2}-e^{-4sT_2})\left(\frac{1-e^{-sh_2}}{s(s+1)}\right) -$$
$$-[1-e^{-(2s+0,5)T_2}(1-e^{-sT_2})-e^{-4sT_2}]\frac{1-e^{-h_2(s+1)}}{(s+1)[1-e^{-T_2(s+1)}]}$$

The Laplace p transformation for the corrected target signal can be obtained using the following equation:

$$X(s) = X_{p1}(s) Y_2(s). \tag{22}$$

Having defined the original of equation (22), parameters of the target signal can be defined.

The offered intelligent processing principle of measurement results in energy saving systems will allow the consumers and the operator to obtain more complete knowledge for the monitoring, control and regulation of technological processes and objects, but non-processed information rather misinforms and disorientates than informs or takes away uncertainty about the features of a situation or about the value of knowledge in relation to accuracy of consumption quantity by consumers of energy resources in separate new and old households of the communal services system.

The existing state standards for the water and heat energy account in households should be reconsidered, and the flowmeters applied up to now should be exchanged by a new type of home counters – a special intelligent measurement system "Logicor", which in comparison with the presently used water and heat flowmeters increases the accuracy of measurements approximately ten times.

Conclusions

1. Using Laplace transform method, a mathematical model of flowmeter's measuring signal at a uniform and at a non-uniform stream of liquid is offered, which allows increasing the accuracy of the measuring signal.
2. The existing Latvia's state standards and norms for the water and heat energy account in separate households should be reconsidered and all the currently used flowmeters should be exchanged by a new type of intelligent flowmeters, which would allow increasing the accuracy of measurements approximately ten times.

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