Estimation and increase of information measuring systems’ metrological reliability on the designing stage

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Abstract. The paper deals with mathematical modelling application aimed at the estimation and increase of the metrological reliability of the information measuring systems on designing stage. The algorithm of metrological reliability estimation is based on mathematical modeling of non-stationary random processes of temporal variation of the metrological characteristics of the measuring means. There is a discussion of two ways to realize the developed method of increasing metrological reliability of the information measuring systems in the design phase based on mathematical modeling and use of parametric optimization methods. The obtained results make it possible for customer to develop information measuring systems with counted value of metrological reliability and also to form the design decisions in order to make information measuring system with maximum value of metrological resource.

1. Introduction

Nowadays realization of any modern project in the industrial design area is completely impossible without measuring tools application. Currently, among the different groups of measuring devices the use of information-measuring systems (IMSs) is increasing [1]. IMSs are used in any experimental research or manufacturing enterprise. Precision of the got experimental data or quality of the output goods depend on metrological reliability of the used IMS [1, 2]. So, IMS’ complexity and responsibility set the very actual problem to provide high metrological reliability of the used IMSs.

As shown by theoretical and practical researches the most important parts of the measuring devices which are responsible for metrological reliability are generally analog blocks as sensors, amplifiers, converters, etc. [2], which transform analog signals of measured physical values before its conversion to the digital form. Meanwhile, metrological reliability is a basic characteristic of IMS’ quality. Herewith, the main quantitative indicator of metrological reliability is metrological resource determined by the time when the measuring inaccuracy surpasses the acceptable limits [3].

So, the aim of our research was to develop the methods providing estimation and increase of IMS’ metrological reliability on the designing stage with mathematical modeling application. Realization of these methods lets to avoid big financial expenditures and complication of the IMS’ structure.
2. Experimental part

2.1. Estimation of IMS metrological reliability

The metrological reliability of IMS analog blocks was estimated by analytic-probabilistic forecasting based on the mathematical modeling of non-stationary random processes time-dependent metrological characteristics of measuring instruments. The main metrological characteristic of an instrument was measuring inaccuracy $\delta$.

The first step of the algorithm included simulation of the circuitry of IMS analog blocks by the equation (1):

$$\xi_i = F_1\left(\xi_{i0}, \varphi, t\right)$$

where $\varphi = \{\varphi_1, \varphi_2, \ldots, \varphi_m\}$ was vector of environmental factors, $m$ – number of environmental factors, $\xi_i(\varphi, t) – parameter value of the component number $i$, $t$ – exploitation time, and $\xi_{i0} – nominal value of the component number $i$.

Then we developed the mathematical model of functioning analog block. The mathematical model introduced the relation between output $y$ and input $x$ signals, parameters of analog block components $\bar{\xi} = \{\bar{\xi}_1, \bar{\xi}_2, \ldots, \bar{\xi}_n\}$ and environmental factors $\bar{\varphi} = \{\varphi_1, \varphi_2, \ldots, \varphi_m\}$ in the equation (2):

$$y = F_2\left(x, \bar{\xi}, \bar{\varphi}\right).$$

The mathematical model (2) was developed on the base of electric scheme of the block and electric schemes calculation methods. It was necessary to use mathematic formula of explored metrological characteristic $S$ to research block metrological properties. Therefore, the model (2) transformed to the model (3):

$$S = F_3\left(\bar{\xi}, \bar{\varphi}, t\right).$$

Electronic components of IMS analog blocks as capacitors, resistors, chips, etc., have a tendency to aging, it brings deviation of components parameters from the nominal values. It garbled the measuring signal and as a result increased a measuring inaccuracy $\delta$.

The environmental factors (e.g., temperature, humidity, pressure, radiation) effect expedites the degradation processes which progress in the components of IMS analog blocks. It decreases the metrological source as a main parameter of the metrological reliability.

The summarizing mathematical model of the metrological characteristic of analog blocks of IMS (that is an inaccuracy $\delta$) gets the view:

$$\delta(t) = F_4\left(x, \bar{\xi}(t), \bar{\varphi}(t)\right).$$

The developed mathematical model (4) took into account the analog blocks components parameters variation under environmental factors impact. This model was used in the procedure of statistical modeling of metrological characteristic at different time of exploitation. The modeling algorithm consisted of consecutive characteristics calculation of the distribution mechanism of the components parameters values of the designing analog blocks and metrological characteristics modeling at the different time moments.

The mathematical model describing variation of time-dependent metrological characteristics was translated into analytical complex equations of mathematical expectations $m_{i\varphi}(t)$ variation in time functions and functions describing the variation in time of possible values borders for metrological characteristic deviations from its mathematical expectation $\psi_{i\varphi}(t)$ was built on the base of the statistical modeling results:
\[
\begin{align*}
\psi_{\pm \sigma}(\tilde{\phi}, t) &= m_{\delta}(\tilde{\phi}, t) + c \cdot \sigma_{\delta}(\tilde{\phi}, t),
\end{align*}
\]

where \( c \) was a coefficient which depends on the level of the trust probability \( P \), \( c = 3 \) if \( P = 0.9973 \).

The developed mathematical model (5) was the basis for calculation of metrological resource values by extrapolation of the equations (5) on future time in exploitation area. Exactness of the prediction results depended on the exactness of the using mathematical models (1) for analog blocks components and also on adequacy of built mathematical models of metrological characteristics.

2.2. Increase of IMS metrological reliability

IMS metrological reliability was increased through the growth of the metrological resource via the algorithm presented on the Figure 1.

There were two possible ways to increase the metrological reliability of IMS analog blocks:

- optimal choice of nominal components providing the highest level of metrological resource under static environmental conditions, and

- optimal choice of exploitation conditions (environmental factors \( \dot{\phi} = \{\phi_1, \phi_2, \ldots, \phi_m\} \)) for a basic components and general analog blocks giving the highest level of the metrological resource of the developed analog blocks.

The mathematical form of this task was:

\[
\begin{align*}
\hat{t}_r &= \max \left\{ \min_{l=1,\ldots,L} \{t_{rl, \text{max}}\} \right\} \quad \text{if} \quad \delta_l(t, \tilde{\xi}, \tilde{\phi}) = \text{var},
\end{align*}
\]

\[
\tilde{\phi} = M, \quad y_l(t, \tilde{\xi}, \tilde{\phi}) \in A_l
\]

where \( y_l(t, \tilde{\xi}, \tilde{\phi}) \) – output characteristic of analog block number \( l, l = 1, 2, \ldots, L \) – number of analog blocks in the information-measuring system; \( \delta_l(t, \tilde{\xi}, \tilde{\phi}) \) – measuring inaccuracy of analog block number \( l \); \( \tilde{\phi} \) – vector of environmental factors; \( M \) – range of possible environmental factors values; \( \tilde{\xi} \)
–vector of components parameters values; \( A_l \) – diapason of correct output signal values of analog block number \( l \); \( t \) – exploitation time moment; \( t^* \) – metrological resource of information-measuring system.

The most appropriate way to solve the task described by the formula (6) was the parametrical optimization method since it provided the max value of the metrological resource by modeling components parameters values and exploitation conditions.

Statistical modeling of the accuracy \( \delta \) for the researching analog blocks included analog block parameters components modeling based on change time-depended values and environmental factors impact and modeling of the researching metrological characteristic realization at different time \( \delta(t_k), k = 0, 1, \ldots, K \) (\( K \) – the number of the time points which the metrological characteristics).

The last step of the algorithm is developing the mathematical model of the change in time process of the metrological characteristic (5) for each analog block is developed. Then the original metrological resource value of the researching analog block is defined by extrapolation of parameters \( m_0(t) \) and \( \psi(t) \) on the area of the future exploitation.

2.3. Approbation of the developed algorithms

The developed models were realized and helped to find optimal values of component parameters \( \bar{\xi}_{\text{opt}} \) and environmental factors \( \bar{\phi}_{\text{opt}} \) for each IMS analog block. Firstly, we defined the most important components of the block parameters and vital environmental factors. Then, the selected parameters were processed by the method of configurations (Hooke-Jeeves method) [4]. The research procedure of the maximum value of the metrological resource was realized using the searching method of configurations.

The important part of the algorithm is control of the functionality condition of the analog block on each step of the algorithm:

\[
y(t, \bar{\xi}, \bar{\phi}) \in A
\]

the \( y(t, \bar{\xi}, \bar{\phi}) \) output characteristic of the analog block, \( A \) is the diapason of the correct output signal values of the analog block.

For the approbation we used voltage frequency converter as typical analog block which enters into the composition of various IMSs. Here we have chosen environmental factors having impact on block metrological resource as temperature \( T \), humidity \( F \), pressure \( P \) and radiation effect \( E \) and the initial values of these factors: \( T_0 = 20 \, ^\circ\text{C}, F_0 = 45 \, \% \), \( P_0 = 1 \, \text{atm} \), \( E_0 = 50 \, \mu\text{R/h} \). Also there were defined the most valuable of these factors: temperature \( T \) and humidity \( F \).

Then the value of metrological resource corresponding to initial factors was calculated as 40500 hours by equation (2). The detailed calculations were missed in this article because it introduced in the article [5]. Time-depended inaccuracy variation before and after developed method application is shown on the Figure 2.

We found the optimal values of the chosen most valid factors: optimal temperature \( T_{\text{opt}} = 15 \, ^\circ\text{C} \) and humidity \( F_{\text{opt}} = 25\% \). These environmental factors values provide the maximal value of the metrological resource of the voltage-frequency converter: 46800 hours. The maximum inaccuracy value is 5 % (Figure 2).
Figure 2. The calculated metrological reliability of block parameters and environmental factors: $\delta$ – inaccuracy value, $t_r$ – metrological resource value, $t_{r_{\text{max}}}$ – metrological resource maximum value, $t$ – time, $h$ – hours, $T_0$ – initial value of temperature, $F_0$ – initial value of humidity, $P_0$ – initial value of pressure, $E_0$ – initial value of radiation, $T_{\text{opt}}$ – optimal value of temperature, $F_{\text{opt}}$ – optimal value of humidity, $m_0$ – mathematical expectations, $\psi_{\pm}$ – metrological characteristic deviations from its mathematical expectation.

Conclusion
The searching algorithm of the optimal values of the components parameters and the algorithm of the environmental condition optimization which provide the maximum level of metrological resource are developed in this article.

We can make a conclusion that realization of the offered algorithms of the metrological reliability increase of the analog blocks of the IMS which includes mathematical modeling on the designing stage of the analog blocks makes it possible to increase the metrological resource as a main characteristic of the metrological reliability more than 10%.

The obtained results make it possible for customer to develop IMSs with counted value of metrological reliability and also to form the design decisions in order to make information-measuring system with maximum value of metrological resource. What is more, realization of these methods lets to avoid big financial expenditures and complication of the IMS’ structure.

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