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ASSESSMENT OF SENSORS LIFETIME ON THE BASIS OF TEST RESULTS

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Abstract – New design-experiment method for forecasting and assessing the sensor reliability on the basis of processing the results of accelerated tests of the production prototypes is considered. The suggested method was developed on the ground of [1-3] and was tested when analyzing the sensor reliability.

Keywords: sensors, accelerated tests, metrological reliability

1. INTRODUCTION

Safety of industrial machinery and transport depends, to a great extent, on the reliability of measuring instruments embedded in equipment.

This problem is particularly important for sensors that are embedded in nuclear reactors or spaceships where an access to sensors is extremely restricted. Measuring instruments must be continuously in a good metrological state during a long lifetime that depends on destination of the equipment (lifetime is equal to 10-30 years).

At that, a supplier should guarantee relying on the sensor tests a high level of the metrological reliability of sensors during their operation, which should be specified by the quality control system.

In this case tests have some specific features. The test time is much less than the lifetime. The acceleration coefficient must be high (about 50 to150), whereas the number of the tested sensors is relatively small due to the cost of the sensors.

However, we have no information about engineering methods of assessing the reliability parameters because of the above mentioned limitations.

Design-experiment method of sensor reliability assessment and forecasting, developed as evolution of methods for forecasting reliability parameters of mechanical components and units [1-3], is suggested.

2. THE GENERAL CONCEPTS

According to [1, 2], the key concepts for produce element reliability are those of failures and damages that can take place under the influence of the corresponding degradation process.

Fig. 1 shows the average time variation of the object state parameter and the upper and lower bounds of the dispersion.

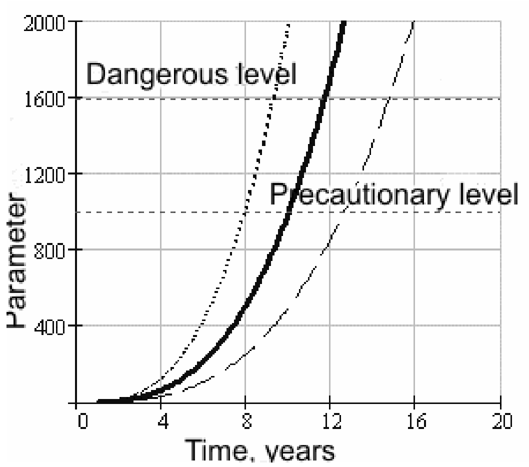

Fig.1. Time variation of the object state parameter

As it follows from Fig.1, a failure is an event associated with transition of an object to a faulty state due to the fact that the characterizing parameter exceeded the dangerous (critical) level of the limiting state.

To prevent this situation, it is desirable that the object state parameter should not exceed some precautionary level. This precautionary level depends on “the engineering reserve” and is called the assigned level of the limiting state.

As the natural dispersion of the degradation process characteristics is inevitable, the durability of a product should be forecasted using the assigned level of the limiting state for the permissible probability γ_{per}.

Usually γ_{per} = 0,8 – 0,99, and it is much smaller than the permissible value for the reliability function (0,99 – 0,9999), which corresponds to exceeding the critical level of the limiting state.

To evaluate if a sensor is in a good metrological state it is suggested to use the modulus of a measurement error as a diagnostic parameter because this diagnostic parameter changes with the degradation of the distribution average and/or dispersion of a measurement result.

A failure of a sensor is an event associated with the transition of the sensor to a faulty state due to the fact that the modulus of an error has exceeded its critical value.

To forecast the reliability of sensors some precautionary error value (PEV) should be assigned. This value is less than the critical error value. At the same time, monitoring of an overall error can be substituted by monitoring its most “dangerous” component (which is predominant or tends to quick growth) or by monitoring the totality of “dangerous” components [4].

Such replacement allows increasing noticeably the cost efficiency of the accelerated tests, because it is difficult and hardly worthwhile to reproduce the full totality of the factors affecting the sensor during its operation.

To discover a “dangerous” component of the error or their ”dangerous” totality is one of the most important stages of accelerated test preparation. It should be carried out during the preliminary research.

This stage includes studying the expected operation conditions as well as theoretical and experimental research into sensor metrological characteristics, into the correlation between them and the influencing factors and into the influences of the accumulation of after-effects.

In some cases it is necessary to single out some parameter that would characterize these “dangerous” components under measurement conditions chosen for accelerated tests.

The duration T of operation on reaching PEV that must be guaranteed by a supplier at the permissible probability γ_{per} is called a lifetime. During this period the sensor must be characterized by a metrological good state.

It is proposed to make the substantiation of the guaranteed sensor lifetime on the basis of accelerated tests results using calculations of the gamma-percentile life $R(\gamma)$.

We would like to remind that the gamma-percentile life is the operating time during which a parameter of an object (in the considered case it is the modulus of the error) will not exceed PEV with the probability equal to γ- percentage [1].

So, the purpose of accelerated tests, in fact, is forecasting the lifetime on the basis of gamma-percentile life evaluation taking into account the strategy of maintenance works for the equipment (this is the object of finite use) where sensors are embedded.

To assess this characteristic, it is necessary (in addition to the accelerated tests results) to have information about the following quantities:

- value of PEV - Δ_{per}
- assigned sensor lifetime - T_{asl},
- specified probability that $\Delta < \Delta_{per}$ - γ_{per}
- specified reliability function P_{per}.

While forming a plan for carrying out accelerated tests of sensors the impact of influencing quantities, which, as a rule, causes degradation of the sensor metrological characteristics during their operation should be provided for.

These factors and the periodicity of their impact in the process of operation should be revealed at the stage of the preliminary research.

One of the peculiarities of the suggested method is the fact that tests are proposed to be carried out by cycles. Therefore, in order to evaluate the durability of a production is suggested to use non-dimensional characteristic N for the useful life (equal to the number of impact cycles).

The number of cycles N that the sensor must stand during the tests depends on the impact of influencing factors in the process of operation taking into consideration the strategy of the maintenance works.

If the duration of cycles in the process of operation is t_o the dimensional durability T can be estimated by (1):

$$T = N t_o \tag{1}$$

This approach has fundamental importance for accelerated tests based on the measurements that are carried out after each cycle of tests at the specified spectrum S_f of the forced load. This spectrum is connected with the spectrum of the load S_o during operation by the forcing coefficient K_f, which is expressed by the following conventional formula:

$$K_f = S_f / S_o \tag{2}$$

The forcing coefficient is necessary in order to calculate the acceleration coefficient K_a that characterizes the functional dependence of the operation cycle duration t_o and the acceleration test cycle duration t_a.

3. THE PROCEDURE OF ACCELERATED TESTS

According to the suggested method, a set of sensors of n in number (n=7-10) must be exposed to the spectrum of the forced load. For example, in the case of a resistance thermometer the spectrum of the load could be as follows: a) repeated slow heating (up to the high temperature, allowed by the specifications), long exposure and slow cooling, b) a totality of thermal treatments characterized by fast heating and fast cooling, c) vibration of the sensor.

The type and form of the load spectrum, the forcing coefficient and the duration of the accelerated test cycle t_a are set taking into account peculiarities of the sensor design and the mode of operation for the object of finite use. It can be carried out at the stage of the preliminary research.

An important part of the test plan is preparing accurate and trustworthy methods and instruments in keeping with the world's standards as well as the recruiting of the staff having necessary qualifications.

For example, when researching reliability of resistance thermometers of A and B classes to forecast their lifetime, it is necessary, in addition to auxiliary instruments, to use the following high accuracy measuring instruments:

- a measuring installation to measure the resistance of a sensitive element (error of measurement not exceeding $5 \bullet 10^{-4}$ Ohm);
- a first class reference thermometer (error of measurement not exceeding $2 \bullet 10^{-3}$ °C at 0 °C;
- thermostats (error being up to $(1-2) \bullet 10^{-2}$ °C).

Evaluation of the error for all the sensors from the set is carried out after each cycle of tests. It makes it possible to receive input tabulated data and to find a correlation between the error and the number of cycles *N*.

The obtained data should be previously checked to exclude failures of sensors and discrepant data.

Taking into account the limited number of sensors being tested even only one failure means that the reliability of the whole set is impermissibly low.

In this case it is necessary to find out the reasons of the failure and to make a decision as to the correction to be maid in the design of the sensor or regarding technology of its producing or the checking of the quality of measurements.

If failures concerned only one component or unit and the necessary correction admittedly does not change the reliability of the other components of the sensor, the calculations of the reliability function can be done thereupon with the use of the purported censored sample [3].

Then the assessment of the durability of sensors by estimation of the gamma-percentile life is carried out. It should be done both in the case of removing from the sample the discrepant data and data on the failures of sensors and after including the data on the sensors for which the above mentioned correction has been done.

4. THE PROCEDURE FOR ASSESSING THE NON-DIMENSIONAL GAMMA-PROCENTILE LIFE

To assess the non-dimensional gamma-percentile life (that is expressed in terms of the number of the impact cycles) a novel procedure was developed and tested. Generally, it consists of the following sub-procedures:

1. For each test cycle *i* the sample of the modulus of errors is formed and the distribution average $M\Delta i$ and variation coefficient Vi are calculated.

2. Using $M\Delta i$ and Vi parameters of one of the two-parameter distribution: a scaling parameter *a* and a parameter of form *b* are calculated.

The preceding analytical research has shown that for the sensor tests it is expedient to choose the logarithmically normal distribution law, because it ensures the largest reserve of reliability for subsequent calculation procedures.

Then using the statistical moments the desired parameters can be expressed by the following formulas [1]:

$$b = \sqrt{\ln\left(1+V^2\right)} \quad ; \quad a = M\Delta \exp\left(-\frac{b^2}{2}\right) \tag{3}$$

3. The conditional probability λi of exceeding Δper for each cycle *i* can be estimated. It is carried out by assessing quantiles for the desired probability by (4):

$$U_{\lambda i} = \frac{1}{b}\ln\left(\frac{a_i}{\Delta_{\partial on}}\right) \Rightarrow \lambda_i \tag{4}$$

The probability λi assessed in this way, in fact, is equal to the metrological failure rate in the non-dimensional system of test cycles Ni.

It allows finding correlation between λi and Ni. Investigations have shown that a good correlation consistency can be received using the power function like this:

$$\lambda(N) = C\,N^m, \qquad (5),$$

having the constant multiplier *C* and the constant power *m*.

If the dispersion is large enough ($V>0,5$) and if there is no evident drift of the measurement results (the correlation coefficient is rather small - < 0,5) the following equality is valid:

$$\lambda(N) = \lambda_0 = const\,. \tag{6}$$

4. To receive the distribution function for the probability of non-reaching the assigned level of the limiting state the classical integral of reliability was applied:

$$\gamma(N) = e^{-\int_0^N \lambda(N)dN} \tag{7}$$

At the power function (5), the solution of the equation corresponds to the Weibull law for the scaling parameter *A* and the parameter of form *B* [1].

$$B = m+1, \quad A = \left(\frac{B}{C}\right)^{\frac{1}{B}}. \tag{8}$$

At the constant metrological failure rate we receive the exponential law with parameters $B = 1$ and $A = 1/C = 1/\lambda_0$..

$$\gamma(N) = e^{-\lambda_0 N} \tag{9}$$

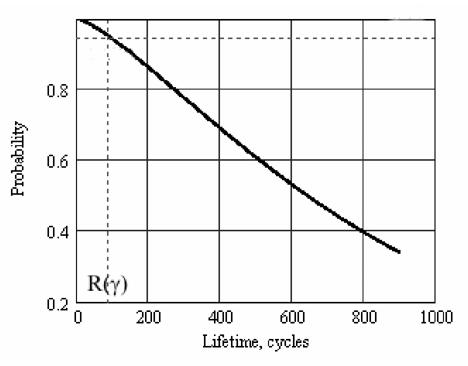

Fig.2. The distribution function

5. After assessing the parameters of distribution the gamma-percentile life can be calculated:

$$R(\gamma) = A\left(\ln\frac{1}{\gamma_{per}}\right)^{\frac{1}{B}} \tag{10}$$

The obtained value of gamma-percentile life is expressed by the number of conventional impact cycles that affected the sensor before it reached PEV at the specified probability γ_{per} (Fig.2).

Upon processing the sensor test results it is suggested to plot the lifetime of the sensor (in a number of impact cycles) against the modulus of the error and permissible probability γ_{per}. This functional dependence can be the general (passport) nomogram.

When researching the reliability of specific sensors, this problem was solved according to the described method. A number of curves were plotted at several values of probability γ_{per} using multiple-factor correlation analysis.

As a result, the empirical functional dependence of the non-dimensional gamma-percentile life on the modulus of the error and the permissible probability γ_{per} with coefficients *m, k1, k2, k3* and *k4*:

$$R(\Delta,\gamma) = k_1 \cdot \Delta^{k_2} \ln\left(\frac{1}{\gamma}\right)^{\frac{1}{k_3 \cdot \Delta^{k_4}}} \tag{11}$$

In accordance with this equation that is consistent with the experimental data the desired nomogram for the specific sensors has been plotted (Fig.3).

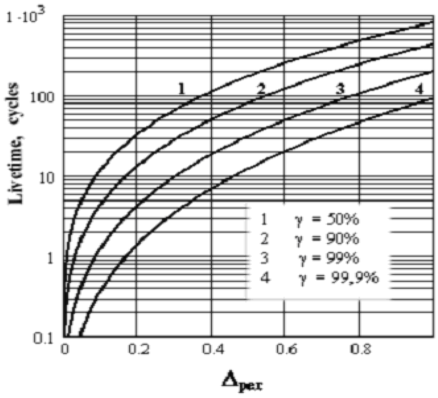

Fig.3. The nomogram for the sensor lifetime
(The error is shown in terms of relative units)

The assessment of the gamma-percentile life allows evaluating evenly the quality of sensors at the comparative tests of different variants of the sensor performing (for example, according as they are modernized).

5. EXAMPLE OF USING THE PROCEDURE

The methodical recommendations were given a work-out through the accelerated tests of resistance thermometer.

The results obtained by testing three sets of sensors were produced for statistical analysis. Each set consisted of 7 sensors and was tested by three cycles of influencing factor impacts. The duration of every cycle was equal to 120 h.

The statistical data treatment was made in accordance with the method considered using the MATHCAD software.

Table 1. Calculation results

	Values	set No1	set No2	set No3
Paremeters of (3)	*a* for the 1st cycle	0,028	0,024	0,025
	a for the 2nd cycle	0,033	0,033	0,034
	a for the 3rd cycle	0,035	0,033	0,036
	b	0,639	0,706	0,506
Paremeters of (11)	m	4	4	4
	k1	791,3	202,9	193,5
	k2	1,869	1,358	1,274
	k3	2,925	3,311	6,194
	k4	0,212	0,219	0,33
Results	*R(95%)*, cycles	22,5	12,3	20,5

The main results of reliability assessment and the forecast of the lifetime for each sensor set are described below. Analysis was made at the PEV and a the assigned lifetime T_{asl} taking into account that γ_{per} = 0,95 and P_{per} = 0,999

At the first stage, the obtained data were checked to exclude failures of sensors and discrepant data. It was found out that failures (the reason was connected with breaks of leading wires) happened only in the third set of sensors. Two failures took place there and, as a result, P= 0,71. It is much less than P_{per} = 0,999. On that ground the manufacturers faced the problem of finding out and eliminating design-manufacturing defects of sensors.

Then, for each set of sensors the statistical moments were calculated – the distribution average and variation coefficient. Next, on the basis of these data the gamma-percentile life was assessed. The results of calculations are given in Table 1.

It follows from the table that the sensors of the first set prevail as far as durability is concerned, because they have the largest 95% life expressed in terms of the number of test cycles.

6. PROBLEMS RELATED TO ASSESSMENT OF THE SENSOR LIFETIME

The above mentioned life measure $R(\gamma)$ has an independent significance for the sensor quality assessment, when comparative tests are conducted.

However, as a rule, it is not sufficient for the customer, because the latter needs to know the lifetime guaranteed by the supplier (producer).

In this connection, the main problem is to develop the method for evaluating the forcing coefficient K_f and the acceleration coefficient K_a.

It is obvious that such a problem should be solved individually for each type of sensor taking into account its design, manufacturing technology and operation conditions, at the stage of preliminary research.

This research should be aimed at studying the physics of the corresponding degradational processes including consequences (after-effects) of various influencing factor (types of loads) impacts upon the metrological characteristics of sensors.

The important part of such researches is to arrange acquisition and processing of information about the experience of a prolonged sensor operation.

Taking into account a small number of sensors being tested, the error of experimental evaluation of the dependence of K_a and K_f is associated, to a great extent, with production standards.

Just cultural standards determine, to a considerable degree, the reliability measure dispersion for the sensors manufactured using this technology.

If the dispersion is large, the trustworthiness of the expected sensor lifetime obtained during the tests will be low.

Therefore, before the accelerated tests, it is necessary to conduct tests confirming the stability of the manufacturing technology.

It should be noticed that the dependence of the acceleration coefficient and the forcing coefficient usually is non-linear.

For example, if the lifetime is determined by metal fatigue the corresponding dependence follows the power function.

The acceleration coefficient estimation should base upon the experimental research of several sets of sensors, produced using the same manufacturing technology.

The dependence of the modulus of the error and the number of influencing factor cycles should be taken. For example, it is convenient to carry out a serious of tests with the load being increased.

According to these data, the dependence of the non-dimensional life and a load can be plotted. After approximation, extrapolation of the obtained curve to the area corresponding to the operation conditions can be fulfilled.

The ordinate of the curve in this point corresponds to the non-dimensional lifetime. Its dimensional value can be calculated according to (1).

In order to estimate the reliability of the sensor the obtained lifetime should be compared with the assigned lifetime T_{ofu} of the object of finite use.

The guaranteed durability of the sensor can be found to be sufficient if (12) is fulfilled:

$$T\ (\Delta,\gamma) \geq T_{ofu} \tag{12}$$

The ratios of the ordinate of the curve at the load that corresponds to the operation conditions and of those at the other loads determine the acceleration coefficients.

As an illustration characterizing the required accuracy of measurements at this stage, we would like to notice that in one of the experiments with the resistance thermometers while the forcing coefficient changed from 1,2 to 2, the acceleration coefficient according to (13) changed from 7 to 300 (Fig.5).

$$K_a\left(K_f\right) = \ K_f^{\,m\cdot k2}\ \ln\left(\frac{1}{\gamma}\right)^{\frac{1}{k3\cdot\Delta^{k4}}\left(\frac{1}{K_f^{\,m\cdot k4}}-1\right)} \tag{13}$$

The process of accelerated testing allows not only assessing the drift of the sensor error.

If it is found out according to the test results that the assessed life is smaller than the required one, the obtained data will facilitate the search of design and technological drawbacks. Elimination of them will make it possible to provide for the required reliability.

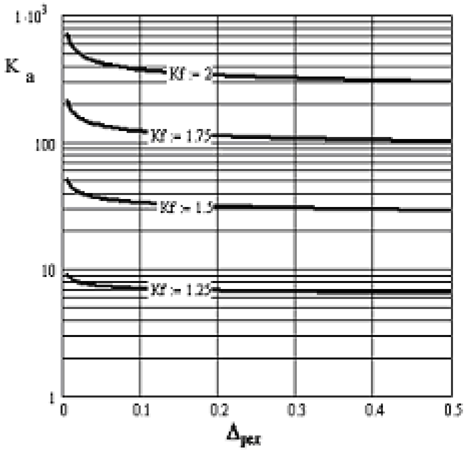

Fig.5. The example of estimation
of the acceleration coefficient
(The error is given in terms of relative units)

The follow-up tests of the sensors of the same type can be conducted at the one value of load using the acceleration coefficient that had been determined earlier and (14):

$$T\ (\Delta,\gamma) = K_a(K_f)t_a\ R(\Delta,\gamma) \quad (14)$$

7. CONCLUSION

The probability-cycle approach shown in this paper has allowed to pioneer a working method for forecasting the gamma-percentile life using the results of tests obtained for several sets of sensors.

The first research carried out using this method has shown that the described methodical principles can be efficient for assessing a large variety of sensors.

However, taking into account that the number of tested sensors is small and the acceleration coefficients are large, the authors would like to emphasize that the error in estimating the gamma-percentile life and lifetime is rather large. This circumstance makes it expedient to recommend the use of intelligent sensors with automated control of the metrological serviceability for the systems of responsible application [4].

The application of the described approach to the lifetime assessment along with intellectualization of measuring instruments makes it possible to increase confidence in the reliability of measurement information coming from the sensors.

The beginning of methodical assurance and software, developed when carrying out this research allows setting the problem of developing an international documentary standard for the rules of forecasting the sensor lifetime.

This standard would make it possible to increase the reliability and comparability of the sensor test results obtained by independent users.

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