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INFORMATION AND MEASURING SYSTEMS FOR EQUIPMENT ADAPTIVE ACCELERATED LIFE TESTS

Г. Оборський, Ю. Паленний, С. Поліщук, І. Прокопович. **Інформаційно-вимірювальні системи для прискорених адаптивних ресурсних випробувань обладнання.** Стаття присвячена постановці завдання щодо удосконалення методів прискорених ресурсних випробувань промислового обладнання, а також задачі розробки інформаційно-вимірювальних систем для отримання статистично значимих даних вимірювань у ході ресурсних випробувань. Визначення ресурсу устаткування може бути проведено шляхом підконтрольної експлуатації. Показано складнощі реалізації такого методу. Застосовуючи метод прискорених ресурсних випробувань, вирішується завдання скорочення термінів випробувань, проте виникає завдання визначення математичної моделі зміни параметрів прогнозування ресурсу. Показано проблеми, пов'язані зі складністю прогнозування ресурсу обладнання за даними прискорених ресурсних випробувань; проблеми з визначенням математичних моделей прогнозування ресурсу різних елементів устаткування, а також устаткування загалом. Наведено приклади математичних моделей оцінки ресурсу для таких елементів як: підшипники, лопатки автомобільних турбокомпресорів, ущільнень та кілець ущільнювачів. Показано, що зношування таких елементів обладнання може бути описане різними математичними моделями, які враховують, як специфічні властивості конструкції, так і особливості умов їх експлуатації. Вказано, що в міру проведення прискорених ресурсних випробувань можна уточнювати математичну модель прогнозу і, що для ухвалення рішення про заміну моделі змінення контрольованого параметра повинно боти статистично значущим. Складність вибору моделі, що описує ресурс обладнання, пов'язана з необхідністю контролю великої кількості параметрів, проведенням статистичної обробки результатів вимірювань, управлінням впливом на об'єкт, що випробовується, і аналізом результатів такого впливу. Вказано, що перерахований комплекс дій можливий при використанні спеціально розроблюваних для цього інформаційно-вимірювальних систем.
Ключові слова: прискорені ресурсні випробування, математична модель, прогноз, точність, надійність, вимірювання, моніторинг

H. Oborskyi, Yu. Palennyy, S. Polishchuk, I. Prokpovych. **Information and measuring systems for equipment adaptive accelerated life tests.** The article is devoted to the formulation of the problem of improving methods for accelerated life tests of industrial equipment, as well as the problem of developing information and measurement systems for obtaining statistically significant measurement data during life tests. The service life of equipment can be determined through controlled operation. The difficulties of implementing such a method are shown. Using the method of accelerated life tests, the problem of reducing test time is solved, but the problem arises of determining a mathematical model for changing parameters to predict the life. The problems associated with the complexity of predicting equipment life using data from accelerated life tests are shown; problems with defining mathematical models for predicting the service life of various equipment elements, as well as equipment in general. Purpose, examples of mathematical models for resource assessment are given for such elements as bearings, blades of automotive turbochargers, seals and o-rings. It is shown that the wear of such equipment elements can be described by various mathematical models that take into account both the specific properties of the structure and the peculiarities of their operating conditions. It is indicated that as accelerated life tests are carried out, the mathematical forecast model can be refined and that in order to make a decision to change the model, the change in the controlled parameter must be statistically significant. The complexity of choosing a model that describes the equipment life is associated with the need to control a large number of parameters, carry out statistical processing of measurement results, control the impact on the test object and analyze the results of such impact. It is indicated that the listed set of actions is possible using information and measuring systems specially developed for these purposes.
Keywords: accelerated life tests, mathematical model, forecast, accuracy, reliability, measurements, monitoring

1. Introduction

Drawing up schedules of preventive repairs requires knowledge of the average time between failures of individual parts or components of equipment, as well as the working life of the equipment. The difficulty in estimating working life and time between failures is associated with the lack or insufficient amount of data necessary for a reliable forecast. For a reliable forecast, it is necessary to have a large amount of data on changes in the most important parameters of equipment during operation. Such data can be obtained, for example, by monitoring changes in these indicators during operation [1]. In addition to monitoring changes in equipment parameters, it is also necessary to monitor differences in the operating conditions of individual pieces of equipment to be monitored [2]. Monitoring is usually carried out using the method of controlled operation of equipment. Using this method, you can obtain the most adequate information about changes in monitored indicators characterizing equipment wear [3].

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With the use of inexpensive microcontrollers connected to the global Internet, the task of controlled operation for some types of equipment can be significantly simplified. For example, microcontrollers such as ESP8266, which are used for Internet of Things technologies for remote monitoring and collection of data on the condition of equipment, can continuously receive measurement data from sensors and transmit this data to a server for collecting and analyzing measurement information. The use of this technology requires a constant connection of the microcontroller to the Internet [4]. However, this method has significant disadvantages [5], which include:

– duration of the information collection process;

– the need to collect and process large amounts of data;

– the need to integrate various sensors into the equipment;

– the need for regular disassembly of equipment in operation for inspection;

– the inability to completely eliminate the accidental impact of unexpected impacts on equipment during operation (special factors), which are not typical for most cases of operation;

– controlled operation is quite difficult to implement both technically and organizationally.

2. Analysis of literary data and formulation of the problem

If special factors are not taken into account, then the problem of predicting wear can be solved through accelerated life tests.

There are known methods for conducting accelerated life tests, in which a reduction in the testing time of controlled objects is ensured by increasing the intensity of the impact of operational factors or by increasing the sensitivity of equipment elements to degradation [6, 7].

When conducting accelerated life tests, it is necessary to take into account the available data from controlled operations, if where are any. The collected data is used to select an adequate mathematical model that describes the dependence of the change in the parameter by which the operating life of the equipment is determined on time. However, some types of equipment may have complex characteristics of such dependencies, which makes it difficult to create accurate mathematical models for predicting time between failures [8, 9].

When reducing testing time by increasing the intensity of the impact, a number of problems arise that require resolution, for example: it is necessary to know the dependence of the service life of equipment parts simultaneously on the time and intensity of the impact; the likelihood of missing potential problems increases; insufficient information necessary to forecast the long-term prospects of equipment operation. It should be taken into account that with an increase in the load on the test object, equipment failure may occur rather than increased wear. In other words, the dependence of wear on the magnitude of the impact often has a non-linear characteristic, and for a reliable forecast it is necessary to know this dependence [10].

Reducing testing time by increasing the sensitivity of equipment elements to degradation is also associated with uncertainty factors such as:

– before testing, it is necessary to have reliable data on the dependence of increased wear on additional factors that lead to increased degradation;

– it is necessary to take into account the complexity of degradation of interconnected equipment elements;

– it is necessary to be able to influence at the sensitivity of equipment elements to degradation, taking into account ensuring the operability of the equipment as a whole.

Due to the complexity of implementing the method of reducing test time by increasing the sensitivity of equipment elements to degradation, this method is used extremely rarely in mechanical engineering.

To successfully apply the accelerated life testing method, by increasing the intensity of the impact of operational factors on the test object, you need to know the answers to the following questions:

– which mathematical model most adequately describes the dependence of equipment parameters on the equipment operating time;

– how the object is affected by various factors affecting the equipment;

– what is the impact of uneven wear of various equipment elements on the service life of the equipment as a whole;

– how it is necessary to take into account the different wear of parts made of different materials when intensifying the impact on the test object;

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– due to which, in order to obtain a reliable forecast of parameter changes in the future, it is possible to increase the accuracy of the measurement results of parameter changes.

From the above it is clear that the reliability of the forecast based on the results of accelerated life tests, in particular, depends on the adequacy of the chosen model for changing the properties of the test object. To increase the reliability of the selected model, the cross-validation method is used, which consists of cross-checking the model when testing several objects. This method is quite labor-intensive, and its implementation is associated with high costs for testing several objects.

Selecting a mathematical model for predicting wear from accelerated tests is a complex task because the wear of different pieces of equipment can be described by different models, such as linear, power, exponential or dependence or described by a polynomial n-th degrees.

In preparation for accelerated testing, based on a thorough analysis of the design, operating instructions, and technical specifications of the equipment, potential factors affecting the operating time of this equipment are identified, parameters that require monitoring are selected, and control points for these parameters are determined.

Of course, the opinion of equipment experts and engineers with experience in operating a specific type of equipment should be taken into account. Expert opinions are especially important when determining external factors that influence the operating life of equipment.

The following shows what mathematical models are used to predict the wear of such equipment elements as bearings, automotive turbocharger blades, seals and o-rings.

For example, to predict the wear rate of bearings, various mathematical models are used that describe wear depending on specific factors. Thus, the wear rate can be expressed by the formula [11]:

$$R = A \cdot t^B \cdot C,$$

where R – generalized indicator of bearing wear;

t – operating time;

A, B, C – parameters that may depend on specific conditions, bearing type and other factors.

In real conditions parameters A, B, C can be determined based on experimental data or analytical models that take into account specific factors such as load, rotation speed, lubricant type, etc. More complex models are known, which are described by the Weibull law [12]. This model takes into account the influence of various parameters, such as load, speed, bearing dimensions, etc. In general, generalized wear can be described by the formula:

$$R = A\left(\frac{C}{F}\right)^n \left(\frac{IN}{D}\right)^p t^q,$$

where F – load;

IN – speed;

D – bearing diameter;

A, C, n, p, q – model parameters.

To assess the wear of automotive turbocharger blades R use similar models, for example [13]:

$$R = A \cdot t^B \cdot C \cdot (T)^D \cdot (N)^E,$$

where t – operating time;

T – temperature;

N – rotation speed;

A, B, C, D, E – parameters that depend on specific conditions, type of compressor and turbine, blade material and other factors.

The intensity of metal corrosion is described by the empirical formula [14]:

$$R = A \cdot t^B \cdot C,$$

where A, B, C – parameters depending on corrosion conditions, material and chemical characteristics of the environment.

Other mathematical models are also used to assess the intensity of corrosion, which include exponential functions that take into account the dependence of corrosion on the concentration of aggressive elements in the environment [14]:

$$R = A \cdot It\,is^{B \cdot t},$$

where $It\,is$ – exponent basis;

A, B – parameters depending on specific conditions.

The wear rate of seals and o-rings is best described by an exponential function similar to the wear rate of bearings, where the parameters A, B depend on specific operating conditions, material type, seal characteristics and other factors [15].

As you can see, mathematical models that describe the wear of individual equipment elements are empirical, and therefore, for their correct application, a deep understanding of wear processes is required both for each element separately and in relation to each other.

3. The purpose and objectives of the research

Selecting the best forecasting model can be implemented using various statistical models and machine learning algorithms, based on the results of which a model is selected that best describes a specific type of equipment.

As accelerated testing is carried out, the mathematical model can be refined as new measurement data is obtained. In this way, the selected model adapts to a specific type of equipment and to changing test conditions. In this way, a mathematical model can be selected that most adequately reflects the wear process.

To make a decision to change the forecasting model, it is necessary to take into account the uncertainties in the measurement results of the controlled parameters. Making a decision to change the model is possible only when statistically significant changes in the controlled parameters are obtained.

The resulting mathematical models for predicting the working life must be constantly compared with the results of ongoing accelerated life tests in order to confirm the compliance of the selected mathematical model with the physical processes occurring with the equipment being tested. Despite the fact that any mathematical model cannot accurately describe the wear process, the mathematical model obtained during the selection will gradually approach the model that most adequately describes the physical wear processes. This method of life testing can be called adaptive accelerated life testing of equipment.

4. Results of research on the selection of controlled indicators

When planning adaptive tests, it is necessary to carefully determine the list of controlled indicators. You should select those indicators that have the greatest impact on the service life of the equipment. The correctness of the choice of test conditions must be assessed according to criteria describing the most common operating conditions. The test results must contain descriptions of the operating conditions for which these conclusions are valid. Such conditions may include:

– temperature fluctuations;
– vibration and shock loads;
– quality of fuel, oil, water or other consumables;
– regularity of service;
– frequency of extreme operating conditions;
– value and frequency of changes in operational loads;
– interaction with equipment external to the test;
– weather conditions including: temperature, rain, snow, icing, ultraviolet radiation, frequency of temperature transition through zero degrees Celsius.

As can be seen from the above, to build a mathematical model of wear, it is necessary to take into account many factors, each of which has its own characteristics, depending both on the design of the equipment being tested and on operating conditions, while one should not forget about the influence of increased loads during accelerated tests.

It should be noted that testing will inevitably produce measurement data with some uncertainty. A preliminary analysis of measurement uncertainty can be a determining factor when planning test duration. Of course, the greater the measurement uncertainty, the longer it will take to test to obtain statistically reliable data.

The construction of a reliable mathematical model, with the help of which it is possible to predict the resource of a test object, can represent: a joint process of monitoring changes in indicators; training this monitoring system by dynamically adjusting the load during testing, making decisions based on statistically significant changes in the controlled parameter and selecting a mathematical model that

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best describes the change in the controlled parameter. The process of adaptive accelerated life tests will be accompanied by the constant collection of measurement data, their processing and analysis in order to refine the mathematical model of parameter changes for prediction.

The mathematical model should be refined only based on changes in the equipment parameter δx, which are statistically significant. Therefore, at the end of each test cycle, the measurement of the parameter δx, which is the difference between the mathematical expectation of the parameter at the beginning of the test cycle $\overline{X}_1$ and in the end $\overline{X}_2$ (see Figure 1) must be assessed for statistical significance.

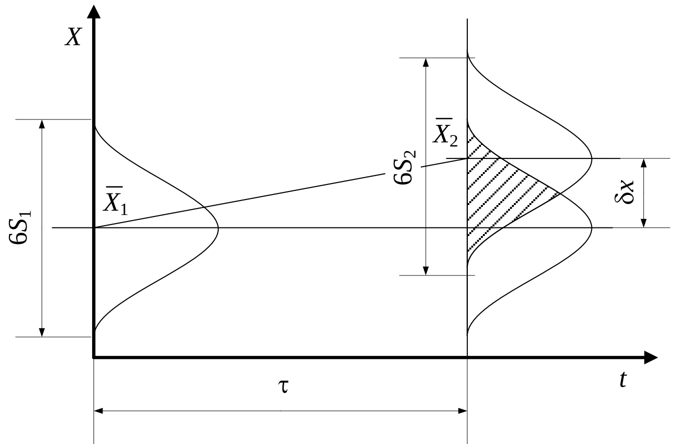

Fig. 1. Change in the average parameter value during testing

A general approach to concluding whether a change in a parameter value is statistically significant is to perform a statistical test such a t-criterion Student's test or z-criterion Fisher, followed by comparison of the obtained p-significance level with the selected level. To effectively apply these tests, one of the requirements for the source data is that the sample averages of these data must have a normal distribution, and with a small sample, all measurement data must comply with the normal law. The degree of compliance of the measured value with the normal distribution law also requires confirmation, for example, by using the Pearson goodness-of-fit test.

Conclusions

Assessing the statistical significance of a change in a parameter, as well as assessing the normality of the distribution of the initial data, requires obtaining and processing large volumes of measurement data during testing, and this in turn requires the creation of special information and computing systems that can ensure the collection and processing of a large amount of measurement information in the real time. Automation of the process of collecting measurement information and the speed of its processing will improve the accuracy of equipment service life forecasting, as well as reduce testing time.

Sensors of information-measuring systems can monitor indicators such as temperature, vibration, pressure, power consumption and other parameters that can characterize the degree of equipment wear and, accordingly, the remaining working life. It should be taken into account that the sensors installed on the equipment should not have a significant impact on the measured object. Where possible, it is necessary to resort to non-contact measurement methods.

Currently, SCADA (Supervisory Control and Data Acquisition) systems are widely used to collect and analyze data on equipment operation. SCADA systems are commonly used in industry to monitor and control production processes. The development of microprocessor technology, in particular microcontrollers, allows testing laboratories to independently develop information and measurement systems to solve specific problems, for example, carrying out adaptive accelerated life tests of equipment.

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