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RELIABILITY PREDICTION OF A MECHATRONIC HYDRAULIC DRIVE AT THE EARLY DESIGN STAGES

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Abstract. The article deals with the reliability of technological machines that use hydraulic feed drives. A priority task in mechanical engineering is the design of mechanical systems with higher stability, reliability, and performance. Various mechatronic systems are used to solve this problem, including mechatronic motion modules for hydraulic drives of technological machines. It is noted that the study of the reliability of mechatronic systems presents a special problem since the interaction of mechanical, hydraulic, and electronic systems gives rise to some new aspects of the theory of reliability. The main technical solutions for reliability incorporated in the design directly impact the machine's functional and economic characteristics. When predicting reliability at an early stage of design, there is the greatest uncertainty (entropy) in assessing the possible states of the machine. As an object of study, a mechatronic hydraulic drive is considered an electro-hydraulic motion module, which can be used in feed drives for heavy metal-cutting machines or industrial robots with a large load capacity. An important parametric characteristic of such a drive is the positioning accuracy of the working body, its stability, and the preservation of values within the specified limits over time. A review of the methodology for assessing and predicting the reliability of mechanical systems is carried out. It is noted that several statistical methods require the accumulation of test results for serial models or prototypes, but many important factors may not be taken into account. The purpose of this article is to obtain the results of predicting the parametric reliability of mechatronic hydraulic drives by using the method of expert assessments (rank correlation) at the early stages of design. This method is based on the ability of independent experts (qualified experts in the field) to provide useful information in the face of quantitative uncertainty. When setting the problem of predicting reliability, the factors that affect the positioning accuracy of the hydraulic drive were ranked in order of importance (ranked). An analytical relationship was established between the weight of the factor and its number in the series. The arithmetic mean weight, the mean relative weight, the standard deviation of the factors that affect the parametric reliability of the drive, and the coefficient of variation are determined. The consistency of expert opinions was shown based on heuristic indicators using the concordance coefficient (Kendall criterion). The considered technique can be used to predict and evaluate the reliability of mechatronic systems that are being developed for use in various fields of technology.

Keywords: reliability prediction, mechatronics, method, factor, rank, hydraulic drive, expert evaluation.

Introduction

The current trend in the design and manufacture of industrial equipment is the use of a mechatronic approach and a block-modular principle. Modern hydraulic drive systems for technological machines are equipped with mechatronic motion modules. This is a synergetic set of hydromechanical, electrical, electronic components, information, and software tools that implement the achievement of a given controlled movement. The predominant area of their application is machines and mechanisms with large masses of working bodies that operate in reverse motion cycles with significant accelerations. Reliability is one of the main indicators of the technical level, quality, and competitiveness of machines that are manufactured using mechatronic modules. It is defined as the ability to perform the specified functions while maintaining the values of the established performance indicators over time within the specified limits that meet the required modes and conditions of use, repair, storage, and transportation. The drive is an integral part of the machine or process equipment, and its reliability is laid down at the design stage, provided in the production process, and maintained at a given level during operation. Reliability prediction is concerned with predicting the behavior of a drive in the future depending on changes in parameters and operating conditions by solving a probabilistic problem. Based on the prediction results, it is possible to control the reliability in fine-tuning prototypes and operating serial machines.

Problem Statement

To date, in various fields of science and technology, there are many methods for predicting reliability, which differs in the set of tasks being solved and the features of the mathematical apparatus used.

Depending on the availability and volume of information used for prediction, these methods can be divided into three groups:

– modeling methods that are used when there is a sufficient amount of statistical data on the change in the state of similar objects during operation;

– methods based on extrapolation and used in cases where there are sufficiently complete data, but the general patterns of changes in the state of the object during operation are unknown;

– expert evaluation methods are used in cases where there is no reliable information about the object and data on changes in its state during operation.

At the design stage, reliability is determined based on design modes and operating conditions that correspond to the drive circuit and the reliability indicators of the elements. For this purpose, apply prediction methods for statistical models; methods of heuristic prediction (expert evaluation.); combined methods. Statistical prediction methods are based on extrapolation and interpolating predicted reliability parameters obtained from preliminary studies. The method is based on the regularities of changes in machine reliability parameters over time. Prediction models are built according to data on reliability indicators and parameters of analogous objects using known statistical methods.

Heuristic prediction methods are based on the statistical processing of independent estimates of the values of the expected reliability indicators (individual evaluations for the object being developed), which are developed by a group of qualified experts based on the information provided to them about the object, its operating conditions, the planned manufacturing technology and other data available at the time of the evaluation. After setting the task of predicting an object, the ranking (arrangement in a row) of factors that affect its reliability is performed [23]. A group of independent experts is being formed (the recommended number is from 5 to 10 people). Experts assign each factor an appropriate weight (rank). The estimates of all experts are summarized in a matrix of weights (ranks). A survey of experts and statistical processing of individual prediction indicators is carried out by methods generally accepted in the expert evaluation of any quality indicators (for example, the Delphi method).

Combined methods are based on the combined application of the above methods, followed by a comparison of the results. At the same time, heuristic methods are used to assess the possibility of extrapolating statistical models and refining the prediction of reliability indicators based on them. The use of combined methods is advisable in cases where there is reason to expect qualitative changes in the level of reliability of objects that are not reflected by the corresponding statistical models, or when the number of analog objects is insufficient for the use of only statistical methods. Depending on the task of reliability analysis and the available amount of a priori information, one or another method can be used. For example, the method of block diagrams is used in the analysis of reliability concerning sudden failures of hydraulic drives. The simplest methods of prediction are known: by constructing dependability change curves, Markov approximation, and the method of expert evaluations.

The most effective is the independent assessment method or the rank correlation method, which is advisable to apply to solve the following problems [12]:

1) prediction development prospects, justifying the development of new schemes and improving drive characteristics;

2) finding reliability indicators in cases where it is impossible to use other methods for which it is necessary to have a priori information;

3) ranking random variables in order of significance.

The increasing integration of electronics and software into mechanical and hydraulic structures is leading to the emergence of an increasing number of new functions, which causes an abrupt increase in the complexity of both individual components and their interconnections. To achieve the normalized (required) indicators of reliability of mechatronic hydraulic drives, it is required not only to search for technical solutions that are aimed at ensuring reliability in specific operating conditions but also to solve the problem of their behavior in the future. Therefore, the importance of reliability prediction as the basis for the formation of a strategy to improve it is increasing.

In this regard, the consideration of methods for predicting the reliability of mechatronic hydraulic drives, especially at the early stages of design and their application in practice, is an urgent task.

Review of Modern Information Sources on the Subject of the Paper

The general provisions of the reliability theory of machines, technological systems, and equipment are considered in [1–3]. Attention is paid to methods for calculating operational reliability indicators from statistical data [4] and reliability applications based on design optimization in engineering structures [5].

Many papers consider private methods for predicting and analyzing reliability using examples of various objects.

A method for predicting the reliability of the hydraulic system of a CNC honing machine based on information about the working condition is presented in [6]. The application of the method based on the Monte Carlo model for predicting reliability is considered in the article [7]. Reliability prediction by this method makes it possible to reveal the statistical nature of the process, and the loss of performance of the product and to evaluate the specific weight of the influence of individual factors.

Article [8] presents a methodology for using Bayesian networks in the field of reliability, and article [9] proposes to analyze the reliability assessment based on a fault tree. Methods for predicting and evaluating reliability at the early stages of designing technical systems are considered in [10, 11].

The works [12–15] describe methods of applied reliability theory, technical diagnostics of hydraulic and pneumatic drives, and consider physical and analytical models of failures, methods for calculating and predicting reliability indicators, and their relationship with economic efficiency.

The use of the Markov approximation method with a piecewise linear approximation based on the processing of statistical data is shown in [12] using the example of predicting the wear of working elements of axial piston machines. An example of predicting the reliability of a generalized hydraulic drive with high pressure by the method of independent expert evaluation or the rank correlation method is also considered. The works [13], [16] give examples of predicting the reliability of a labyrinth-screw pump using the methods of Markov approximation and expert assessments. Examples of using the method of block diagrams to compare the reliability of different schemes of hydraulic drives are shown.

The article [17] is devoted to the problems of assessing the reliability of mechatronic hydraulic units at the design stage. An example of assessing the reliability of rotation hydraulic units at the design stage is shown in the article [15]. Features of the design implementation and construction of mathematical models of work processes in hydraulic devices of mechatronic systems and electro-hydraulic mechatronic motion modules and recommendations for calculating their main parameters and characteristics are given in [18], [19, 21]. The issues of evaluating and predicting the reliability of these devices are not considered.

In other areas of technology, in addition to traditional methods of predicting reliability, methods are considered based on the use of artificial neural network technology by establishing a functional relationship between equipment defects and the probability of failure. For example, in the article [20], an adaptive system for predicting technological equipment's reliability is proposed, based on a neural network model consisting of three subsystems – monitoring, adaptation, and prediction.

Objective and Problems of Research

As the information sources' analysis shows, the methodological foundations of reliability prediction have already been laid by now, but specific (engineering) prediction methods have not yet been sufficiently developed. Some of the existing methods of statistical interpolation are not very suitable for mechatronic systems with different physical natures of their components, since, as a rule, they have significant individual features. In particular, this is due to the peculiarities of stochastic processes [21]. Since mechatronic systems are innovative developments, in many cases, they may not have analogs. In the absence of information about the testing of prototypes, it is advisable to predict reliability by the method of expert assessment.

This article aims to obtain the results of predicting the parametric reliability of mechatronic hydraulic drives by using the method of expert assessments at the early stages of design.

Main Material Presentation

The object of research is a mechatronic hydraulic drive, the schematic diagram of which is shown in Fig. 1 [21].

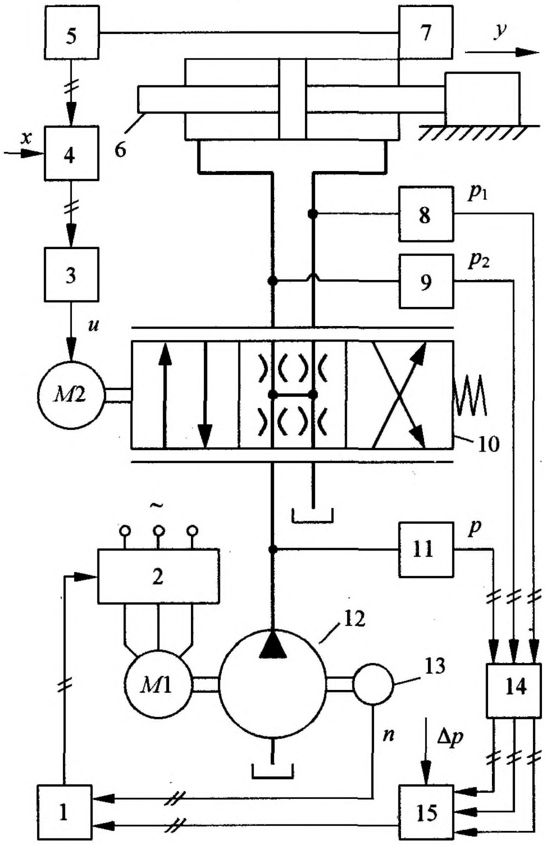

Fig. 1. Schematic diagram of a mechatronic hydraulic drive
1 – speed controller; 2 – frequency converter; 3 – stepper motor control unit;
4 – block of the operational control system; 5 – normalizing transducer;
6 – hydraulic cylinder; 7 – position feedback sensor; 8, 9 and 11 – pressure sensors;
10 – throttling hydraulic valve; 12 – pump; 13 – tacho-generator;
14 – measuring block; 15 – block adder

In the circuit diagram, speed controller 1 controls the frequency converter 2 of the asynchronous motor *M*1. Pump 12 supplies the working fluid through the throttling valve 10 to the executive hydraulic cylinder 6. The signal about the displacement of the hydraulic cylinder rod y from the position feedback sensor 7 through the normalizing converter 5 is transmitted to block 4 of the operational control system, which receives the input signal x.

The control signal from block 4 is fed to block 3 for controlling the stepper motor *M*2. With the help of a screw mechanism, the rotation of the stepper motor shaft is converted into a linear movement of the spool of the throttling distributor 10. The speed of the pump shaft 12 is controlled using a tacho generator 13. The pressures of the working fluid p_1 and p_2 in the cavities of the hydraulic cylinder, as well as the supply pressure p are measured by pressure sensors 8, 9, and 11. The signals from these sensors are fed to the measuring unit 14, and then to unit 15, which is supplied with a predetermined value of the differential pressure Δp. The resulting signal is sent to controller 1. The scheme can be converted into a rotary-type hydraulic drive. To do this, instead of a hydraulic cylinder, it is necessary to use a hydraulic motor with a feedback sensor (for example, a circular photoelectric converter).

The considered hydraulic drive as an electro-hydraulic motion module can be used in feed drives of heavy metal-cutting machines or industrial robots with a large load capacity. Accuracy characteristics are the main indicators that determine the capabilities and scope of the machine, and the level of its quality. An important parametric characteristic of such a drive is the accuracy of positioning of the working body of the machine or robot, its stability, and the preservation of values within the specified limits over time.

To predict the parametric reliability of a mechatronic hydraulic drive by the method of expert assessments, a group of five (n = 5) specialists (experts) with experience in the design and operation of hydraulic systems was involved.

In the first stage, the experts identified the factors that, in their opinion, can most significantly affect parametric reliability. These factors (m = 4) include:

1) errors of the converter with the control system;
2) errors of the displacement sensor;
3) leakage of the working fluid through the gaps in the throttling valve;
4) wear of the screw and nut of the screw mechanism.

The selected factors represent the characteristics of the mechanical, hydraulic, and electronic components of the mechatronic hydraulic drive.

In the second stage, the experts, independently of each other, assigned each factor (characteristic) a weight φ_i from 1 to 0 according to the decreasing degree of its influence on the parametric reliability. It is assumed that the true (real) value of the weight of each factor is within the range of estimates and that the generalized collective opinion is quite reliable. The weights $\varphi(i, j)$ assigned by the experts to each factor are presented in Table 1.

Table 1

Weights, arithmetic mean weight, average relative weight and standard deviation of factors that affect drive reliability, and coefficient of variation

Number expert, i	Factor number (characteristics), j			
	1	2	3	4
1	1.0	0.6	0.9	0.8
2	0.9	0.5	0.8	1.0
3	0.7	0.4	0.7	0.9
4	0.4	1.0	1.0	0.8
5	0.6	0.5	0.8	0.9
Estimated values				
$\bar{\varphi}(i,j)$	0.72	0.6	0.84	0.88
$\varphi_0(i,j)$	0.237	0.196	0.274	0.287
σ_j	0.214	0.210	0.102	0.209
v_j *100 %	29.73	34.96	12.13	23.77

In the method of expert assessments, there are two ways of processing the opinions of experts. One of them is based on the application of the usual methods of mathematical statistics. The second way is heuristic. Experts are presented with a sequence of factors or characteristics they rank by assigning a weight $\varphi(i,j)$ to each i-th factor. Based on these data, it is possible to establish an analytical relationship between the factor's weight and the number it occupies in the ranked sequence.

In the third stage, the weights of the factors were calculated according to the formulas [12], which are given below.

The arithmetic mean value of the weight of the i-th factor according to the opinions of all experts

$$\bar{\phi}(i,j)=\frac{\sum_{1}^{m}\phi(i,j)}{n}, \tag{1}$$

where n is the number of experts; $\varphi(i,j)$ is the weight indicated by the i-th expert on the j-th factor.

The relative average weight of expert assessments

$$\phi_0(i,j)=\frac{\bar{\phi}(i,j)}{\sum_{1}^{m}\phi(i,j)}, \tag{2}$$

where m is the number of estimated factors.

The values of the characteristics obtained by formulas (1), (2) are shown in Table 1.

The arrangement of these characteristics in some factors is already a sufficient reason for ranking the factors, since the arrangement by values $\bar{\phi}(i,j)$ or $\phi_0(i,j)$ indicates the distribution of weights, and, consequently, the significance of the factors.

However, it is of undoubted interest to elucidate the degree of agreement between experts' opinions within the limits of the assessment of each factor. The degree of agreement of experts is estimated by statistical and heuristic indicators. Statistical indicators are dispersion and coefficient of variation.

For each assessed factor, the variance of expert weights was determined [12]

$$\sigma_j=\sqrt{\frac{1}{m}\sum_{1}^{m}[\phi(i,j)-\bar{\phi}(i,j)]^2}, \tag{3}$$

and the coefficient of variation of the j-th factor

$$v_j=\sigma_j/\bar{\phi}(i). \tag{4}$$

The values of statistical indicators obtained from expressions (3), (4) are shown in Table 1.

Dispersion and coefficient of variation are indirect indicators of the consistency of expert opinions on this factor. The smaller the coefficient of variation, the greater the agreement in the opinions of experts. The conclusions about the consistency of experts are formulated based on the total set of characteristics and factors using heuristic indicators. The heuristic indicator is the coefficient of concordance (consistency) or the Kendall criterion W [12], which is determined by the formula

$$W=\frac{12\sum_{1}^{m}d_i}{n^2\left(m^3-m\right)-n\sum T_i}, \tag{5}$$

where d_i is the deviation of the sum of ranks from the arithmetic mean; $d_i=s_i-\bar{s}$ (here s_i is the sum of ranks for the j-th characteristic; $s_i=\sum\rho_i$, where ρ_i is the rank of the weight estimate of the j-th characteristic; $\bar{s}=s/n$); $T_i=\sum_{1}^{L}(t_i^3-t_i)$ – index of the connectedness of ranks (L – number of groups of ranks; t_i is the number of related ranks in the j-th group).

To determine the coefficient of concordance, it is necessary to determine the serial number (place) that this rank has in the ranked sequence of ranks assigned by experts in all factors. If several experts indicated the same weight, the rank is determined as the average value of the corresponding numbers.

Criterion $W = 1$ indicates complete agreement of the opinions of experts, and $W = 0$ indicates complete inconsistency.

The results of calculations related to formula (5) are shown at the bottom of Table 2.

Table 2

The ranks of the characteristics of the factors that affect the reliability of the drive, the sum of the ranks, the deviation of the sum of the ranks from the arithmetic mean, and the indicators of the connectivity of the ranks

	Factor number			
	1	2	3	4
	1.0 1.0	1.0 1.0	1.0 1.0	1.0 1.0
	0.9 2.0	0.9	0.9 2.0	0.9 (2+3)/2=2.5
	0.8	0.8	0.8 (3+4)/2=3.5	0.8 (4+5)/2=4.5
	0.7 4.0	0.7	0.7 5.0	
	0.6 5.0	0.6 5.0		
	0.5	0.5 (6+7)/2=6.5		
	0.4 7.0	0.4 8.0		
Estimated values				
s_i	19.0	20.5	11.5	8.0
d_i	5.25	6.75	-2.25	-5.75
T_i	0	6	6	12

The concordance coefficient calculated by the formula (6) was 0.967. Thus, the opinion of experts is consistent ($W \approx 1$).

The values of criterion W are subject to χ^2-distribution. Expert estimates are considered consistent at a given confidence level $\gamma = 0.95$ if the condition

$$\chi^2_{av} = \frac{12\sum_{1}^{m} d_i}{mn(m+1) - \frac{1}{n-1}\sum T_i} > \chi^2_T(\gamma;\nu), \tag{6}$$

where $\nu = m - 1$ is the number of degrees of freedom; is determined according to the tables [12], [22].

According to table [21], the value of the quantile $\chi^2_T(0.95;\ 4)$ is 4.988. Thus, expert estimates are consistent at a given level of confidence $\gamma = 0.95$.

Conclusions

The analysis of information sources on the reliability of industrial equipment showed that, despite the already existing methodological foundations in this area, it is necessary to search and test various methods for predicting and assessing reliability, especially at the early stages of design. The creation of mechatronic systems requires careful coordination of elements of different physical natures, which should ensure the high-quality performance of the service purpose. In addition, the production of these systems and their components are associated with significant costs, so the development and coordination of components must be carried out at the design stage, taking into account reliability prediction. In the absence or insufficiency of a priori information about the functioning of new equipment with mechatronic modules, the method of independent expert evaluation (rank correlation) is effective.

As a result of predicting the parametric reliability of a mechatronic hydraulic drive by using the method of expert assessments at the early stages of design, among other ranked factors, the fourth option ($j = 4$) received the highest value $\overline{\phi}(i, j) = 0.88$. This gives reason to believe that the wear of the screw mechanism can have the greatest impact on positioning accuracy.

Based on heuristic indicators using the concordance coefficient (Kendall's criterion), the consistency of expert opinions was shown, and by comparing the calculated value χ^2_{av} with the tabular value of the cavantile χ^2-distribution, the consistency of expert assessments at a given confidence level $\gamma = 0.95$ was confirmed.

It should be emphasized that the development of methods for predicting the reliability of mechatronic hydraulic drives will provide a significant economic effect, since, firstly, the time and money spent on testing prototypes will decrease, and secondly, the potential durability of drives will be used more rationally due to the correct organization of the repair and operation system, thirdly, even at the early stages of design, it will be possible to choose the optimal design solution in terms of reliability.

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