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MATHEMATICAL MODEL OF ESTIMATION OF THE QUALITY OF THE APPLICATION OF THE CYLINDER-PISTON GROUP OF THERMAL DIESELS ON THE CRITERIA FOR THE STABILIZATION OF FUEL CONSUMPTION AT THE REAL TIME OF FACTORY TUBE TESTS

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Abstract. In the article, a mathematical model of the evaluation of the quality of running-in of a cylinder-piston group (GPG) based on the criterion for stabilizing fuel consumption in real time for running tests of diesel locomotives on the diesel locomotive frame is considered. The effect on the magnitude of fuel consumption of suddenness is shown to be the inclusion of the disconnection of auxiliary equipment connected to the engine crankshaft via a V-belt transmission and a reducer with a compressor and water and air cooling fans. It was noted that the mathematical modeling of the on-off suddenness, carried out on the basis of the law of normal distribution, did not reveal a significant effect on the criterion of fuel consumption stabilization, with the help of which the quality of run-in was measured.

The influence of the critical state of the precision surfaces of the GPG on the fuel economy of diesel locomotives in operation is considered. The problem of critical wear of the precision surfaces of the cylinder head is considered. It affects the stable working process of the heat engine at practically all speeds of rotation and load, including idle and low load modes (non-nominal modes).

The solution of the problem of the stable working process of the heat engine is constrained by the absence of a theoretically grounded and experimentally confirmed criterion for stabilizing fuel consumption that estimates the quality of the run-in of the cylinder piston group in real time for each mode of shortened run-in tests of the internal combustion engine over the entire range of rotation and load frequencies.

The developed mathematical model presents the main performance indicators of the running-in of the GPG, which ensure a stable workflow in the process of the internal combustion engine. Requirements and conditions for qualitative technology of shortened run-up tests are formulated. A qualitative estimation of the work of the GPG in real time at all speeds and power of the diesel engine is given. The proposed mathematical model is maximally approximated to its use in engineering calculations by the engineering and technical staff of locomotive repair enterprises and locomotive depots.

Key words: fuel consumption stabilization criterion, shortened run-off tests of the GPG, mathematical model, precision surface, wear, diesel, workflow.

The resulted mathematical model allows to estimate quality of running-in of cylinder-piston group by criterion of stabilization of fuel consumption in real time of running tests of diesel locomotives on a diesel locomotive frame. The effect on the magnitude of fuel consumption of suddenness is shown to be the inclusion of the disconnection of auxiliary equipment connected to the engine crankshaft via a V-belt transmission and a reducer with a compressor and water and air cooling fans. It was noted that the mathematical modeling of the on-off suddenness, carried out on the basis of the law of normal distribution, did not reveal a significant effect on the criterion of stabilization of fuel consumption with the help of which the quality of running-in of the GPG was assessed.

When carrying out factory running tests of diesel generators on the diesel locomotive frame, the problem arises of the choice of the criterion for the quality of the running-in of the friction pair in the piston ring-cylinder liner at each run-in test mode in real time.

For the first time, the problem of a well-founded choice of the nomenclature of quality and reliability indicators was put in [1], where it was shown that the solution of this problem should be sought in the way of studying models of quality diagnostics and the influence of quality and reliability indicators on the quantitative characteristics of the process of functioning. In this work, as a general performance evaluation, the mathematical expectation of the income from exploitation is accepted. At the same time, income is understood as a useful return, which can be expressed in monetary or other form. The idea of the possibility of such an approach in solving problems related to ensuring reliability was expressed in [2]. Since the income from exploitation depends on the level of quality and reliability of the product, the selected indicators included in the expression for determining the expected income expectation were called the main ones. It is noted that they should be compared on the quality and reliability of different technologies and technical objects of the same purpose and different versions of the same product.

The analysis of various factors on which the qualitative nature of the work of the product depends, and those that determine the form of the income function and, consequently, the magnitude of its mathematical expectation are singled out.

As the main factors influencing the choice of the type of reliability indicators, it is determined:

Constructive solution factors (adaptability to repair);

• factors of the nature and mode of use of the product for its intended use;

• factors of failure consequences.

By factors of constructive execution of the product are divided into repaired and unreinforced.

According to the principles of limiting the duration of operation, the unmounted products are divided into the following:

• to failure;

• to failure or limit state;

• until the required functions are completed.

Repaired products according to the principles of limiting the duration of operation are divided into the following:

• until the first failure;

• until the first failure or limit state;

• until the first failure or completion of the required functions;

• to the limit state;

• to the limit state in the "standby" mode or to failure or perform the required functions in the "work" mode.

The division of products into repaired and non-repaired is due to the presence of an objective property embedded in the products during the design, regardless of whether the product can be repaired during operation or not.

According to the temporary mode of use, unremovable and repairable products are divided into operating

- in continuous mode;
- in discontinuous mode by regular cycles;
- in intermittent mode by cycles of random duration.

On the event of failure in the process of running-in the cylinder-piston group of an internal combustion engine, the most important is the fact of failure

when the specified functions are executed or not in the specified volume.

When assessing the functional consequences in the process of running-in the cylinder-piston group of an internal combustion engine, the failure events are distinguished by:

-fact of refusal;
- the performance or non-performance of the specified functions by the product in a given volume;
- forced downtime;
- refusal and forced downtime;
- the performance or non-performance of the specified functions in a given volume at an arbitrary time when the "work" begins.

The criterion for choosing a fuel consumption stabilization factor in real time for a running test of an internal combustion engine is to evaluate the functional consequences of failure, which can be estimated by the costs of eliminating the failure and, accordingly, the damage caused.

For all possible combinations of factors characterizing the real modes of running tests, formulas are used to calculate the economic efficiency during the operation of the engine and determine the reliability indicators corresponding to almost any diesel engine.

In accordance with the methodology of shortened run tests, the most significant factors characterizing the running conditions of the cylinder-piston group of the diesel engine on the diesel locomotive frame are determined. In addition, a cipher is compiled, according to which the indices of reliability and reliability are selected. The issue of selection of the quality indicators of the running-in of a cylinder-piston group is considered in accordance with the approved methodology of reduced running tests.

Further development of the method of factory shortened running tests, within the limits of the reduction in the running tests, is possible, in obtaining qualitative parameters of running-in of a pair of friction, a piston ring-cylinder liner with regard to efficiency in operation.

The choice of quality and reliability indicators of technology of reduced running tests of diesel engines is paid the closest attention, since possible failures, for example - jamming of the cylinder-piston group (CPG) failures of the department lead to a total failure of all diesel locomotive systems, thus reducing the operational efficiency [3]. To assess the quality of run-in to the CPU by the parameter of fuel consumption stabilization in real time on each mode of running tests, the functioning of the entire technological system is regarded as a random process $F_z(t) = F[Z(t)]$,

where:*Z(t)*- set of states of the elements of the system.

$F_z(t)$ – a set of states of elements functioning in real time.

The mathematical expectation of the fuel consumption stabilization criterion (1) is taken as the indicator of the quality of the functioning at the time I, and for the performance characteristic of the criterion for the stabilization of fuel consumption, the time interval [a, b] is its mathematical expectation with the output effect of the system on this interval:

Instant indicators of the quality and reliability of the system are defined as the ratio of the performance indicators of the functioning of a real system to the corresponding indicators of an ideal system. Interval indicators are defined as the ratio of the output effect of a real system to the corresponding parameters of an ideal system or averaging in the interval [a, b] an instantaneous reliability index.

In work [4] classification characteristics for the purposes of selection of qualitative indicators of energy-saving technologies (ECT), including technologies of reduced running tests, are considered more fully.

In accordance with the "Nomenclature of energy efficiency indicators and the procedure for their introduction into normative documentation" (DSTU 3755-98) and depending on the composition and characteristics of the tasks to be performed, the quality indicators of energy-saving technologies (ECT)

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are classified according to various characteristics, and not only by the uniformity of properties [5 -9]. Universal signs of classification of quality indicators of ECT as applied to the tasks of providing and assessing the quality of ECTs for shortened run tests are:

-energy efficiency factor of KBE,%;

-specific consumption of energy resource b, J / unit of output (work);

- specific fuel consumption bn, (UT in t) / unit of production (work);
- energy intensity of the basic production assets Eof, J / UAH;
- rated voltage UN, V;
- rated current IN, A;
- frequency f, Hz.

The quality of ECT, depending on the number of indicators, can be presented in the form of single, complex and integral parameters. Depending on the form of representation of the characteristic properties, absolute, relative and specific quality indicators of ECT are distinguished.

Of particular importance are the evaluation indicators, characterizing the economy and manufacturability, i.e. those properties that form the quality parameter of ECT as a technological object of the enterprise railway. transport or operated technological object. Estimated indicators are used to normalize the quality of ECT, assess its technical level in the development and standardization, to verify the quality parameters when it is controlled, tested and certified. According to the evaluation indicators, various ECTs classified as classifiers are classified in terms of manufacturability.

Estimates of the quality of ECT are divided into two groups:

• indicators that are used to compare competing technologies in the market by the degree of customer satisfaction with certain economic or environmental parameters;

• indicators that are used to verify compliance with the requirements of international and domestic standards, mandatory for implementation. First of all, this refers to the requirements for safety and environmental friendliness of ECT.

Estimated indicators are also grouped according to the homogeneity of the characteristics being characterized into three types: functional, resource-saving, nature-conservative.

Indicators of functional suitability characterize the technical essence of technology, the properties that determine the basic functions for which it is designed, i.e. the ability of technology (in our case, ECT) to fulfill its own economic or environmental functions in real operating conditions. By appointment, ECT unites such groups of quality indicators as reliability, ergonomics and aesthetics.

The reliability indicators of energy-saving technology characterize its ability to store real-time operating values within specified limits for the values of all given quality indicators, while observing the prescribed modes and conditions of use in maintenance, repair, etc.

Indicators of ergonomic ECT characterize its adaptability to human use in technological processes of railway transport enterprises.

The esthetics of esthetics of ECT characterize its aesthetic impact on humans and are intended for quantitative and qualitative assessment of aesthetic value, the degree of conformity of ECT to the aesthetic demands of certain groups of consumers in specific conditions of railway transport.

Resource-saving quality indicators of ECT characterize its properties, which determine the level of spent material resources in the creation and operation for the formation, provision and realization of its quality.

The group of resource-saving indicators includes subgroups of indicators of manufacturability of ECT and resource consumption.

Indicators of technological effectiveness of ECT characterize the features of its composition and structure, affecting the level of costs of raw materials, materials, fuel, energy, labor and time in operation.

A special group consists of environmental quality indicators of ECT, characterizing its properties associated with the impact of technology on human beings and the environment in the processes of its implementation at enterprises or technical objects (rolling stock) of rail transport. Environmental quality indicators of ECT are combined into two groups of indicators for safety and environmental friendliness.

Classification indicators are applied to the EST of any kind in question - at enterprises and technical objects (rolling stock) of railway transport, as they determine the areas of its application and conditions of use. Classification indicators play an important role in the identification of products.

Energy-saving technologies of railway transport use indicators of functional suitability, maintainability and manufacturability.

The final choice of the nomenclature of quality indicators for the ECT is made taking into account the requirements of international standards ISO 9000-2001, ISO 9004-2001, ISO / TR 10013: 2003, ISO 19011-2003.

The determining factor in the choice of the estimated quality indicators for ECT is the minimization of the costs for the development, implementation and operation of ECT, while simultaneously improving qualitatively the performance of Russian rail transport in a market economy.

When choosing and determining the criterion for assessing the quality of run-in of a cylinder-piston group, various dependencies and qualitative indicators of energy-saving technologies are considered. The possibilities of maintenance and control of the technology of reduced running tests in real time mode, the nature of the main processes determining the transition of technology to the marginal state, the possibility and method of restoring the technical resource, the availability in the technological hierarchy of computers or other devices of discrete technology are taken into account [11].

Yu.B. Germeier formulated the principle of guaranteed result of the quality of technology (technical object), which is that for this economic efficiency criterion, efficiency evaluation should be based on obtaining the guaranteed (maximally guaranteed) value of the efficiency criterion. With regard to the tasks of ensuring the quality of ECT indicators, this principle is interpreted as comparative in the choice of solutions based on guaranteed values of quality and reliability indicators in real-time operation.

When choosing the criterion for stabilizing fuel consumption, which evaluates the quality of the run-in of the cylinder piston group in real time, it is necessary to take into account that the regimes on which the main run-in of the cylinder piston group (GPG) occurs are non-nominal (n = 300 min-1 - n = 450 min-1) , are characterized by low indicators of the work process. The reason for low indicator indicators is considered to be an unstable fuel supply process, characterized by fuel injection skips and uneven injection of fuel through cycles and cylinders. As a result, - in working cylinders on non-nominal modes, power distributions are constantly occurring at the set load of the running mode. Taking into account this factor, the desire to choose the criterion for the quality of running-in of a pair of friction piston ring-cylinder liner of a GPG in real time of running tests becomes clear.

The choice of the criterion should provide a methodology for non-destructive quality control of the running-in of the GPG in real time on all running tests of diesel locomotives on the diesel locomotive frame. The application of the criterion providing a methodology for non-destructive quality control of the running-in of the GPG is the basis for the creation of a reduced energy-saving technology of factory running tests.

Analysis of previous studies and formulation of the problem

Analysis of the running-in quality of the friction pair "piston ring-cylinder liner" pair of diesel locomotive diesel locomotives on the main, non-nominal running conditions showed that the main influence on run-in has a fuel supply process, characterized by injection skips and uneven injection of fuel in cycles and cylinders. Additionally, the factor of sudden switching-off of auxiliary equipment: compressor, main and additional cooling water cooling circuits of the diesel generator, cooling fans of traction motors, also has an effect.

It is known from literary sources that the factors cited are very negative and their influence (throughout the life cycle) has not been fully studied to the present.

The current practice of assessing the quality of running-in of GPG diesel locomotives in factory and depot conditions is based on methods of destructive testing, which in itself is not only inefficient, but requires large material costs.
A number of researchers used the method of quality control based on selective measurements of fuel consumption. However, in this case, the account of the influence of the on-off of the auxiliary equipment was not applied to the amount of fuel consumption.
As practice has shown, the methods used do not allow to give an accurate estimate of the quality of the running-in of the GPG mirror by the nature of the change in the fuel consumption in real time.

Results of the conducted studies

The mathematical model of the criterion for the quality of run-in to the GPG was developed on the basis of works [12-16], which allowed to substantiate the theory of a stable fuel supply process in the entire range of rotation frequencies and loads of diesel locomotives. Further development of the theory is confirmed by a special design nozzle [17], which in practice ensured a stable fuel supply law in all operating modes of diesel locomotives.

A stable fuel supply law implemented by special design injectors allowed us to justify the mathematical modeling of the criterion that assesses the qualitative side of the running in of the diesel engine's CPU, both at the diesel test station and the diesel locomotive frame, in real time.

The software of the mathematical model is implemented in a certified fuel consumption meter AK-DT 0.5, which allows you to record the moment of stabilization of fuel consumption, chosen by us as a criterion for fuel consumption stabilization (K_g^{est}), in real time on each run-in mode.

The chosen criterion allowed to provide a method of non-destructive quality control of run-in of the GPG in real time at each run-in test mode.

The chosen criterion, having confirmed its effectiveness at the diesel test station, required additional mathematical modeling and refinement of the software, taking into account the suddenness and frequency of switching on and off auxiliary diesel equipment on the diesel locomotive frame and which had never been considered before.

Modeling on-off of auxiliary equipment and their influence on the criterion (K_g^{est}), stabilization of fuel consumption was made on the basis of the law of normal distribution.

At the same time, the mathematical model was optimized taking into account the choice of regimes for short running tests. The software of the developed mathematical model is realized within the framework of non-destructive quality control of run-in of the GPG in real-time tests.

When developing a mathematical model, a special difficulty was created by the apparatus for monitoring and recording the sudden on-time (t_{rec}) switching on / off of the main water cooling fan (t_{cf}) and the brake compressor (t_{bc}).

For this case, the effect on the criterion for stabilizing fuel consumption has the form:

$$Kg^{est} = t_{ex} + \frac{\kappa \cdot r}{r - f_{\text{mod}}}(t_{cf} + t_{bc} + t_{rec}), \tag{1}$$

Where tex - time of running tests; k- the density of the running tests; r is the running time; - part of the operating time of the diesel when the auxiliary equipment is switched on and off suddenly.

Increasing the on-off duration, during useful use, is undesirable since the duration and affects the Kgest.

In the course of the research it was accepted that the law of distribution of the determining parameter (DP) for sudden on-off of various auxiliary equipment is a function of the sudden periodicity of the DP. As the duration of the test increases, the amount of information about the course of the influence of the DP increases, and, consequently, the degree of the random process decreases. To determine the dependence (Kgest) of the resistance of the DP, the sudden on-off delay is approximated by the hyperbolic dependence

$$\sigma_V = \varphi(t_{\text{rec}}) = \frac{1}{p + q_{bc}}, \tag{2}$$

where q is the coefficient characterizing the rate of decrease of the variance

$$p = \frac{1}{\sigma(0)}; \tag{3}$$

In this case, the dependence of K_g^{est} on the on / off time of the auxiliary equipment takes the form:

$$Kge[\varphi(t_{\text{пр}})] = \frac{S_0 - S_{\text{cv}}}{V_2[\varphi(t_{\text{bc}})]}, \tag{4}$$

where S_0 and S_{cv} are the initial and critical values of the DP, respectively; Is the upper bound of the rate of change of the DP.

Thus, the problem is reduced to finding the dependence of the sudden on-off of auxiliary equipment with respect to different laws of the density of the separation of the rate of change in the DP.

In the case of a uniform law of the distribution density, the rate of change in the DP is the expectation and variance of the form

$$m_V = \frac{1}{2}(V_1 + V_2) \tag{5}$$

$$\sigma_V = \frac{V_2 - V_1}{2\sqrt{3}} \tag{6}$$

Thus, the problem of changing in the DP.

In the case of a uniform law of the distribution density, the rate of change in the DP is the expectation and variance of the form

$$\tau = \frac{S_0 - S_{\text{cv}}}{\text{m}_\text{V} + \sqrt{3}\dfrac{1}{p + qt_{rec}}} \tag{7}$$

Equality (7) reduces to the form

$$\tau = \Theta \frac{c_1 + b_1 t_{\text{rec}}}{c_1' + b_1 t_{\text{rec}}} \tag{8}$$

$$c_1 = m_V p;\ \frac{1}{p} = \sigma_V;\ \Theta = \frac{S_0 - S_{\text{cv}}}{m_V},\ b = m_V q,\ c_1' = c_1\sqrt{3}.$$

Similarly, in the case of Simpson's law under

$$m_V = \frac{1}{2}(V_1 + V_2); \tag{9}$$

$$\sigma_V = \frac{V_1 + V_2}{2\sqrt{6}}; \tag{10}$$

$$\tau = \Theta \frac{c_1 + b_1 t_{\text{пр}}}{c_1'' + b_{1t} t_{\text{пр}}}, \tag{11}$$

$$c_1'' = c_1 + \sqrt{6}$$

t_{rec}= 0 for (11) fair

$$\tau = \Theta \frac{c_1}{c_1'}. \tag{12}$$

The curve (11) is an equilateral hyperbola, related to asymptotes whose center of symmetry is shifted to a point with coordinates $\left(-\frac{c_1}{c_1'}, \Theta\right)$.

According to Simpson's law, an analogous expression is obtained with the coordinates of the center of symmetry $\left(-\frac{c_1}{c_1''}, \Theta\right)$.

$$\tau = \frac{S_0 - S_{\text{кр}}}{m_V} \cdot \frac{c_1}{c_1'}. \tag{13}$$

In Fig. 1, 2, which shows the dependencies constructed from expressions (8) and (11) with the values of resistance (Kg^{est}) and the duration of the sudden ON-OFF of the DP.

An analysis of the nature of the dependence (between the stability of the chosen criterion and the duration of switching-on and off of various equipment) carried out in the framework of the formulas below

$$S_0 - S_{\text{кр}} = 5 \text{ con.un.};\ V_1 = 0.01\frac{\text{con.un}}{\text{h}};\ V_2 = 0.08\frac{\text{con.un}}{\text{h}};$$

showed that with the increase in the duration of the sudden on-off of various equipment with the dependence $\tau = f(t_{\text{rec}})$ the stability asymptotically approaches the parameter.

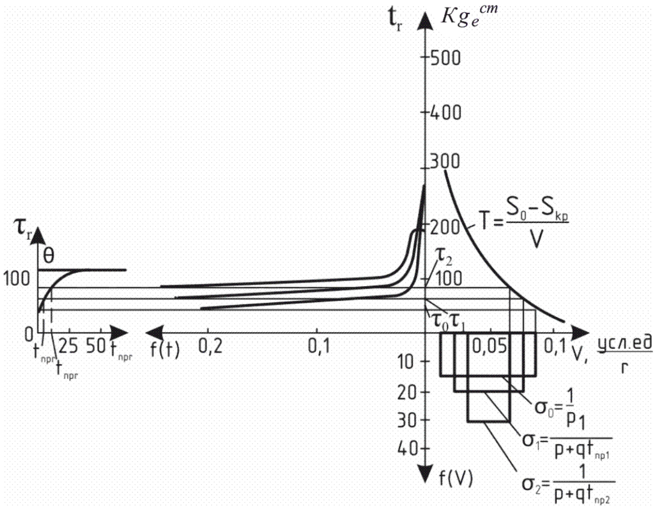

Figure 1. The relationship between the resistance (Kg^{est}) and the duration of sudden on-off of various equipment at a uniform density of distribution of the rate of change in the DP

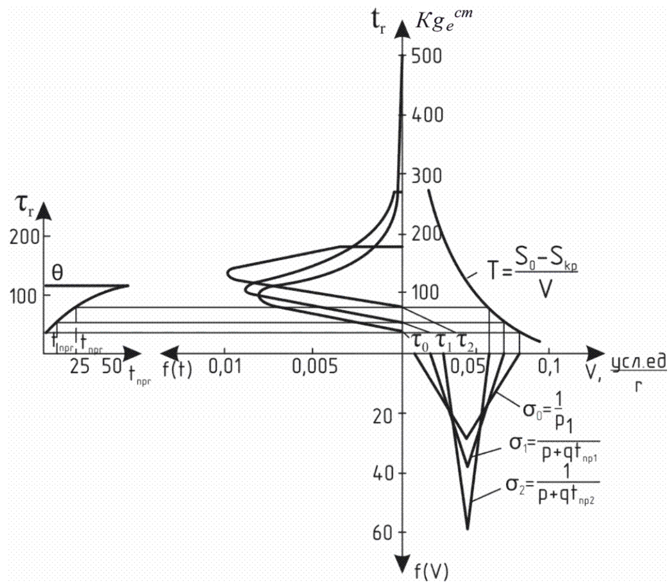

Figure 2. Dependence between the resistance (Kg^{est}) and the duration of the sudden switching on of different equipment with the density of distribution of the rate of change of the DP by the law of Simpson

In the case of a truncated Weibull distribution [18], which is an asymmetric distribution, a decrease in the variance as a result of the sudden on-off of equipment entails a decrease in the mathematical expectation, so that it is difficult to obtain a precise analytical expression of the dependence of the resistance on the sudden on-off of various equipment. Numerical analysis with various variations of the parameters of the Weibull law shows that the dependence of the resistance (Kg^{est}) on the sudden on-off of various equipment can approximately be represented by an empirical relation

$$\tau[\varphi(t_{rec})] \cong \frac{S_0 - S_{cv}}{V_2} + \kappa' t_{rec}, \quad (14)$$

where $\kappa' \cong \frac{a \cdot q}{2}$.

In the distribution of Rayleigh, *a=2,* but with exponential, a=1. Relation (14) is shown in Fig. 3 during $S_0 - S_{cv} = 5$ con.un.; $V = 0.01\frac{\text{con.un}}{\text{h}}$; $V = 0.08\frac{\text{con. un.}}{\text{h}}$; $\Theta = 2;\ q = 2.$

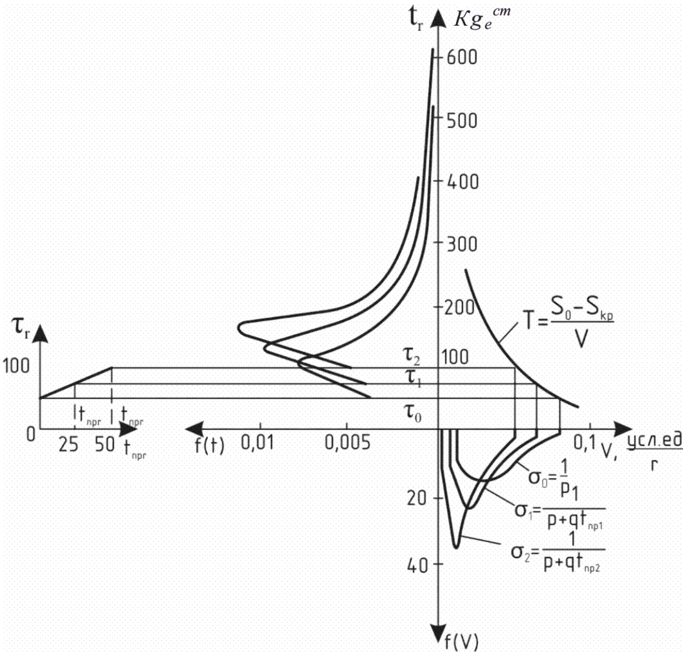

Figure 3. Dependence between the resistance (*Kg*$^{est)}$ and the duration of sudden switching on of different equipment at the rate of change in the rate of change of the DP according to the Weibull law

The dependence $t(t_{rec})$ is a decreasing function from t_{rec} [2] and can be approximated by a function of the form

$$t_B = \frac{1}{c_2 + b_2 t_{rec}}. \quad (15)$$

Using formulas (1), (8), (11), (14) and (15) allows you to get

$$t_и = \Theta \frac{c_1 + b_1 t_{rec}}{c_1' + b_1 t_{rec}} - \frac{\kappa \cdot r}{r - f_{mod}} \left(\frac{1}{c_2 + b_2 t_{rec}} + t_{rec}\right); \quad (16)$$

$$t_и = \Theta \frac{c_1 + b_1 t_{rec}}{c_1'' + b_1 t_{rec}} - \frac{\kappa \cdot r}{r - f_{mod}} \left(\frac{1}{c_2 + b_2 t_{rec}} + t_{rec}\right); \quad (17)$$

$$t_{и} = \frac{S_0 - S_{cv}}{V_2} - \frac{aq}{2} - \frac{\kappa \cdot r}{r - f_{mod}}\left(\frac{1}{c_2 + b_2 t_{rec}} + t_{rec}\right). \quad (18)$$

The useful life $(t_{и})$ has a maximum value $t_{rec} = t_{rec\ opt}$ Value $t_{rec\ opt}$ can be found graphically or as a result of solving equations (16) ÷ (18) to the extremum,

$$\frac{dt_{и}}{dt_{rec}} = 0. \quad (19)$$

Equations (16), (17) reduce to an algebraic equation of the fourth degree, and equation (18) is of the second power with respect to $t_{rec\ opt.}$

So, values $c_2 = b_2 = 0.04\ \frac{1}{h}$, $\kappa = 1$ $q = 1$, $S_0 - S_{cv} = 5_{con\,un}$; $V = 0.01\frac{con.un}{h}$; $V_2 = \frac{con.un}{h}$ It can be determined that for cases (17) и (18) τ_{opt} are respectively equal to 7,0 hand 8,2 h. reduced running tests.

It should be noted that in the proposed mathematical model, the criterion for stabilizing fuel consumption (Kg^{est}) took into account the optimal volume of technological operations, including both the existing methodology and the methodology for reducing short run tests [19].

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