CODEN STJSAO ISSN 0562-1887
ZX470/1610 UDK 531.392:531.314:512.81

Operation Reliability and Diagnostics of Complex Mechanical Systems

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Keywords

Information system
Reliability
Multinomic distribution
Wear mechanisms
Diagnostics

Ključne riječi

Informacijski sustav
Pouzdanost
Multinomna distibucija
Mehanizam trošenja
Dijagnostika

Primljeno (Received): 2012-10-15
Prihvaćeno (Accepted): 2013-01-21

Original scientific paper

Abstract: This paper deals with the use of an information system for the reliability and diagnostics of complex mechanical systems. It includes a theoretical analysis of relations and interconnection of failures of these systems, providing thus simple but sufficient data (type, rate, failure time distribution and operating mode). It deals in more detail with a correlation of simultaneous failures with the use of a multinomic model. The basic theory is reflected in an example, in which failure of plain bearings in a small set of internal combustion engines (2 sets consisting of 7 engines in a laboratory and in routine operation) were studied and 11 fatigue mechanisms (adhesion, abrasion, erosion, fatigue, vibration, cavitations, mix of the above-mentioned mechanisms, peeling off bearing surface layers, corrosion, change of geometric shape and production, technology and assembly inaccuracies) where 35 basic diagnostic features of failures were discovered. Correlation analysis provided to find important relations between the features of failures (in total, 4 important features in relation to the number of hours worked) and to use them as basic diagnostic parameters in operation.

Pouzdanost rada i dijagnostika kompleksnih mehaničkih sustava

Izvornoznanstveni članak

Sažetak: U ovom radu prikazana je uporaba informacijskog sustava za pouzdanost i dijagnostiku složenih mehaničkih sustava. To uključuje teorijsku analizu odnosa i povezivanje kvarova navedenog sustava, pružajući na taj način malo ali dovoljno podataka (vrsta, odnos, distribuciju vremena kvara i način rada). U radu se detaljnije istražuje korelacija istovremenih kvarova s pomoću multinomnog modela. Osnovna teorija je prikazana u primjeru, u kojem su istraživani kvarovi klizni ležajeva u maloj skupini motora s unutarnjim izgaranjem (2 kompleta koji se sastoje od 7 motora u laboratorijskom i uobičajenom radu) i 11 mehanizama zamora (adhezijsko, abrazijsko, erozijsko, zamorsko, vibracijsko, kavitacijsko, kombinacija navedenih mehanizama, ljuštenje površinskih slojeva ležaja, korozijsko, promjena geometrijskog oblika i proizvodnje, tehnologijska i montažna netočnost), gdje je otkriveno 35 osnovnih dijagnostičkih značajki kvarova. Korelacijska analiza osigurava pronalazak važnih odnosa između značajki kvarova (ukupno, 4 važne značajke u odnosu na broj radnih sati), te ih koristi kao osnovne dijagnostičke parametre u radu.

1. Introduction - RDIS

To identify and characterize a universal scheme of Reliability and Diagnostics Information System (RDIS) for a general solution in the field of mechanical systems is practically impossible. Despite this statement, every information system should contain the following information on the operation of any mechanical system [1] (see Fig. 1), for example:

- boundary requirements for a system and its elements,
- list of potential failures, their basic discriminating features, their possible classification (negligible, marginal, critical, catastrophic),
- criteria for classification of failures (time flow, scope, conditions for their creation, occurrence in time, mutual relationship, external indications, causes, mechanisms, remedy complexity, qualitative and quantitative features of failures, etc.),
- diagnostic parameters, used physical methods of diagnostics, methods, methodologies, sensors, diagnostic signals, etc.,
- determination and characteristics of operating mode (continuous, cyclic, operating, general),
- technique of failure data collection in time (time protocol, formalized documents, automatic data collection, coding, classification, filtering, security, etc.),

Symbols/Oznake

RDIS	- Reliability and Diagnostics Information system - pouzdanost i dijagnostika informacijskog sustava	$N_v(T)$	- vector indicating a rate of failures observed in an operating interval <0,T> - vektor pokazatelj omjera kvarova u promatranom intervalu rada <0,T>
$T_{vi}(T)$	- vector indicating a time distribution of failure, type v_i within an interval <0,T> - vektor pokazatelj vremena raspodjele kvara, tip v_i unutar intervala <0,T>	$p_j(i)$	- probability of simultaneous failures v_i and v_j - vjerojatnost istodobnih kvarova v_i i v_j
k	- number of results - broj rezultata		
Mh	- machine hours - sati rada stroja		**Greek letters/Grčka slova**
v_i	- vector indicating type of failure - vektor pokazatelj vrste kvara	Σ	- sum - zbroj
n	- number of independent tests - broj neovisnih pokusa		**Subscripts/Indeksi**
r_{vi}	- characteristic of operating mode - značajka radnog moda	i, j	- ordinal number - redni broj
A_x	- result - rezultat	krit	- critical - kritičan
Z_x	- feature - značajka	výp	- calculated - izračunat

- methodology and analysis of obtained information (software, routine and special outputs, etc.),
- additional information or necessary experiments to explain complex outputs,
- elasticity, effectiveness, integrity, efficiency, compatibility (Microsoft Office, etc.), reliability (ISO 9001), periodical updating, open (modular) design, superstructure availability, departmental solution, etc.
- utilization of RDIS and feedback, etc.

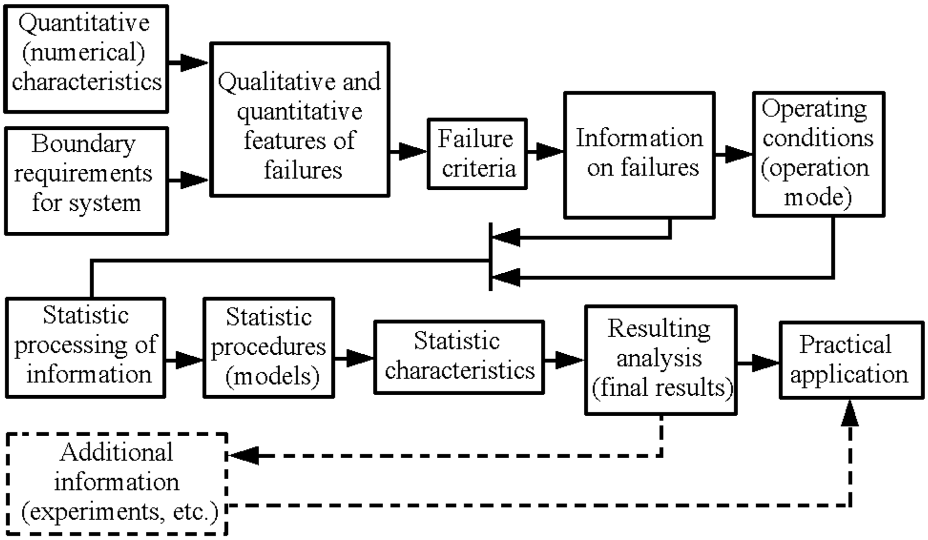

Figure 1. RDIS block diagram

Slika 1. RDIS dijagram

2. Failure relationship analysis

Input information for an analysis of mechanical systems reliability can be presented as a set of vectors [2]: v_i, $n_v(T)$, $t_{vi}(T)$ and r_{vi}, for which it is valid

$$v_i = [v_1, v_2, ,...v_i,...,v_k] \ , \tag{1}$$

$$n_v(T) = [n_{v1}, n_{v2},...,n_{vi},...,n_{vk}] \ , \tag{2}$$

$$t_{vi}(T) = [t_{vi}(1), t_{vi}(2),...,t_{vi}(i),...,t_{vi}(k)] \tag{3}$$

$$r_{vi} = [r_{v1}, r_{v2},...,r_{vi},...,r_{vk}] \ , \tag{4}$$

where is:

- v_i …vector indicating a type of failure,
- $n_v(T)$ …vector indicating a rate of failures observed in an operating interval <0,T>,
- $t_{vi}(T)$ …vector indicating a time distribution of failure, type v_i within an interval <0,T>,
- r_{vi} …characteristic of operating mode.

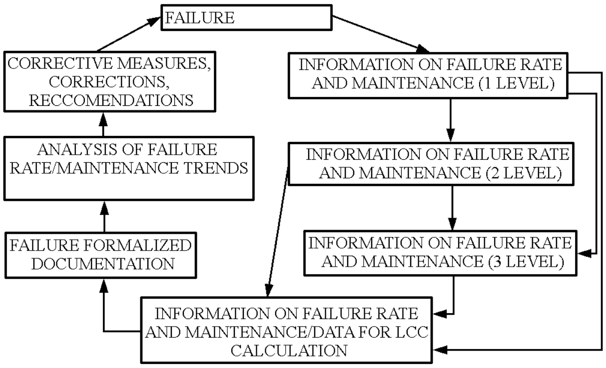

Figure 2. Block diagram of information about failure rate and corrective measures [3]

Slika 2. Dijagram toka informacija o učestalosti kvara i korektivne mjere [3]

To analyze data on mechanical systems presented by vectors $t_{vi}(T)$, i = 1, 2, …, n_i) and r_{vi}, many standard methodologies of tests and assessment [4] can be used, such as:

- Wöhler fatigue tests,
- Weibull fatigue tests,
- Simultaneous fatigue tests,
- Censured fatigue tests according to time or samples,
- Probability models,
- Probability fatigue curves,
- Approximative models,
- Correlation analysis,
- Testing procedures, etc.

For example, an appropriate method is a below-mentioned correlation analysis related to the vector $n_v(T)$, which gives a failure rate identified in the operating interval <0,T>. Let us consider the vector $n_v(T)$, equation (2), which can be written according to a simultaneous occurrence of failures (v_i, v_j) into the matrix

$$\left[n(v_i, v_j)\right] = \begin{vmatrix} n_{11} & n_{12} & \cdots & n_{1j} & \cdots & n_{1k} \\ n_{21} & n_{22} & \cdots & n_{2j} & \cdots & n_{2k} \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ n_{i1} & n_{i2} & \cdots & n_{ij} & \cdots & n_{ik} \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ n_{k1} & n_{k2} & \cdots & n_{kj} & \cdots & n_{kk} \end{vmatrix} , \tag{5}$$

where diagonal elements n_{ii} for i = 1, 2, …, k, determine a rate of independently occurring failures, type v_i, and elements n_{ij} present a simultaneously generated failures [3]. It is valid

$$\sum_{j=1}^{k} n_{ij} = n_{vi} = n_i \tag{6}$$

$$\sum_{i=1}^{k} n_{ij} = n_{vj} = n_j \tag{7}$$

$$\sum_{i=1}^{k} \sum_{j=1}^{k} n_{ij} = n(T) \tag{8}$$

where are:

- the equation (6) … failure rate, type v_i for i = 1, 2, …, k,
- the equation (7) … failure rate, type v_j for j = 1, 2, …, k
- $n_{ij} = n(v_i, v_j)$ … failure rate, type v_i and v_j produced simultaneously,
- the equation (8) … number of all failures, type v_i and $v_i \cap v_j$, for i, j = 1, 2, …, k, within an interval $<0, T>$;

Similarly, we can plot matrixes of simultaneous failures of higher orders [4],

$$[n(v_i, v_j, v_k)], \ [n(v_i, v_j, v_k, v_l)] \text{ etc.,} \tag{9}$$

which provide information on simultaneous occurrence of failures (v_i, v_j, v_k), (v_i, v_j, v_k, v_l), etc.

Independence of failures v_i is defined by the matrix.

$$\left[n(v_i, v_j, v_k)\right] = \begin{vmatrix} n_{v1} & 0 & 0 & 0 & 0 & 0 \\ 0 & n_{v2} & 0. & 0 & 0 & 0 \\ . & . & . & . & . & . \\ 0 & 0 & 0 & n_{vi} & 0 & 0 \\ . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & 0 & n_{vk} \end{vmatrix}, (10)$$

In order to get an information analysis from the matrix (5), we rearrange this matrix into the form of relative failure rates

$$P_j(i) = \frac{n_{ji}}{n_{vi}}, \text{ for } j = 1, 2, \ldots, k_i \text{ and } i = \text{const.} \qquad (11)$$

and we obtain the matrix of relative failure rates, (12)

$$\left[p(v_i, v_j)\right] = \begin{vmatrix} p_1(1) & p_2(1) & \ldots & p_j(1) & \ldots & p_k(1) \\ p_1(2) & P_2(2) & \ldots & p_j(2) & \ldots & p_k(2) \\ . & . & \ldots & . & \ldots & . \\ p_1(i) & p_2(i) & \ldots & p_j(i) & \ldots & p_k(i) \\ . & . & \ldots & . & \ldots & . \\ p_1(k) & p_2(k) & \ldots & p_j(k) & \ldots & p_k(k) \end{vmatrix}$$

Thus, it will hold

$$\sum_{j=1}^{k} p_j(i) = \sum_{i=1}^{k} p_j(i) = 1 \qquad (13)$$

where $p_j(i)$ - probability of simultaneous failures v_i and v_j.

Evidently, these arrangements will lead us to a more general multinonic model and multinonic distribution [2], which is a generalization of binomic distribution [5]. We are to determine a probability of occurrence generally in a final number of phenomena and we consider ***n*** independent tests, all of which end just by one from ***k*** results. Probability of a result A_j equals to π_j regardless of the order of test, which shall be valid for every j, ($j = 1, 2, \ldots, k$). Nevertheless, we are interested in a number of tests n_1 with a result A_1, number of tests n_2, with a result A_2, number of tests n_k with a result A_k. If n_1, n_2, n_k are non-negative integer numbers and if it holds that $\sum_j n_j = n$, then we shall expect n_1, n_2, nk in multinomic distribution with a probability

$$P(n_1, n_2, \ldots, n_k) = \frac{n!}{n_1! n_2! \ldots n_k! (n - \sum_{i=1}^{k} x_i)!} \pi_1^{n_1} \pi_2^{n_2} \ldots \pi_k^{n_k} (1 - \sum_{i=1}^{k} p_i)^{n - \sum_{i=1}^{k} x_i}$$

...(14).

The distribution function of multinonic distribution of simultaneous occurrence of various types of failures provides to calculate strength of a possible stochastic dependence between them. For example, for the first row of the matrix (12) it will hold true that for a correlation of failure, type 1 v_1 with general j-th failure v_j, the correlation coefficient is

$$r_{1j} = -\sqrt{\frac{p_1(1).p_i(1)}{\left[1 - p_i(1)\right]\left[1 - p_i(1)\right]}}, \text{ for } (-1 \leq r_{1j} \geq 1).$$

…(15)

In general, it will hold for any failure pair (v_i, v_j), the correlation coefficient is

$$r_{ij} = -\sqrt{\frac{p_i(i).p_j(i)}{\left[1 - p_i(i)\right]\left[1 - p_j(i)\right]}}, \text{ for } (-1 \leq r_{ij} \geq 1).$$

…(16).

Other potential analysis can refer, for example, to inherent reliability, maintainability and life of sub-components of complex systems when we are looking for statistic models for $F_i(t)$, $R_i(t)$ and $f_i(t)$, which describe properties of elements or failure mechanism that can be identified from the information system. Conclusions are focused on proposal of preventive measures, maintenance optimization or, in general, on a development of an effective program to assure product quality and reliability, etc.

3. Application of monitoring the operation information on failure rate with the use of correlation and regression analysis

Information system of operation reliability and diagnostics [1] modified in accordance with [4] included a study of operation failures of connecting-rod sliding bearings of the internal combustion engines in special equipment. It referred to 12 connecting-rod bearings, the failures of which were caused by the following 11 wear mechanisms. These are:

- Adhesion, which resulted in tearing out and relocation of particles in the Beilby layer due to a close interaction and local adherence during mutual relative movement, vector – v_1,
- Abrasion (knurling, cutting), which resulted in plastic deformation of unevenness of softer surfaces by hard free particles, vector – v_2,
- Erosion resulting in a particle separation and damage (corrugation) of surfaces by foreign particles carried by a flow of lubricating oil, vector – v_3,
- Fatigue, which resulted in the chipping out of material and pitting during contact, probably cyclic fatigue and high shear stress, vector – v_4,
- Vibrations, which resulted in a separation of particles due to mutual alternating vibration tangential motion, probably due to a small

amount of rigidity in the bearing housing with typical red color of product wear, vector – v_5,

- Cavitation, which resulted in a separation of particles and damage to surfaces in the area of impacts caused by disappearing of cavities during turbulent flow of lubricant through irregular spaces in the bearing, vector – v_6,
- Mixture of above-mentioned mechanisms of wear and their mutual interaction together with an influence of the friction corrosion, vector – v_7,
- Peeling off the surface layer of material probably caused by the combustion products and impurities discovered in a lubricant due to insufficient cleaning of air, vector – v_8,
- Corrosion wear or wear caused by a chemical reaction on a working surface (lining) of the bearing with lubricant, vector – v_9,
- Mechanisms of failures caused by changes of geometric shape of working parts during operation (ovality, conicity, etc.), vector – v_{10},
- Mechanisms of failures caused by operating (technological or installation) geometric inaccuracies of the bearing bushing, vector – v_{11}.

For all mentioned mechanisms, typical characteristics (number, shape and size of wear particles, morphology of wear particle surface and worn bearing, etc.) were determined; standards, gauges and decision criteria for assessment of a technical condition in dependence on performance parameter (number of kilometers covered, number of hours worked Mh, fuel consumed, physical age, etc.) were stated. The result of study was to approximately assess a residual life and prevailing mechanism of wear, vector – v_i for i = 1, 2,…, 11. Further solution consisted in identification of 35 basic features $(Z_1 - Z_{35})$, obtained by diagnostics of engines in view, specification of which can be seen in Tab. 1. Character of these features encompasses an initial (running-in) condition and normal working condition when an inherent reliability is reduced to a level of operating reliability in dependence on the performance parameter Z_3. Altogether, 14 combustion engines in two sets were studied, especially during an experiment at the testing shop a set N_{zk} = 7 engines and in a routine operation N_{prov} = 7 engines. Time of operation research $<0, T_{max}>$ was measured in machine hours (Mh), for T_{max} = 4,000 Mh. Diagnostic data on features Z_i for i = 1, 2, …, 35 found at engines during research were presented by two groups of information

$$N_{zk} \ldots Z^{(0)}_{ij(k)} \quad \text{and} \tag{17}$$

$$N_{prov} \ldots Z^{(1)}_{ij(k)} \ , \tag{18}$$

for i = 1, 2, …, 35; j = 1, 2; k = 1, 2, …, 7;

Simple correlation analysis of featured pairs resulted in the matrix correlation coefficients [5] in the form

$$\left[r(Z_i, Z_j)\right] = \left| \begin{matrix} 1 & r_{12} & \ldots & r_{1j} & \ldots & r_{1,35} \\ r_{21} & 1 & \ldots & r_{2j} & \ldots & r_{2,35} \\ \cdot & \cdot & \ldots & \cdot & \ldots & \cdot \\ r_{i1} & r_{i,2} & \ldots & r_{ij} & \ldots & r_{i,35} \\ \cdot & \cdot & \ldots & \cdot & \ldots & \cdot \\ r_{35,1} & r_{35,2} & \ldots & r_{35,j} & \ldots & 1 \end{matrix} \right| \tag{19}$$

Testing of hypotheses of correlation coefficients in accordance with relations

$$H_0 \ldots r_{ij} = r_{ZiZj} = 0 \quad \text{and} \tag{20}$$

$$H_1 \ldots r_{ij} = r_{ZiZj} \neq 0 \tag{21}$$

In accordance with the decision criteria in the form

$$\frac{r_{ij}}{\sqrt{1 - r_{ij}^2}} \sqrt{\nu - 2} = t_{v\acute{y}p} \tag{22}$$

$$t_{v\acute{y}p} \leq t_{krit} \Rightarrow r_{ij} = 0 \quad \text{a} \tag{23}$$

$$t_{v\acute{y}p} \triangleright t_{krit} \Rightarrow r_{ij} \neq 0 \tag{24}$$

for $t_{krit} = t(\alpha_i;\ \upsilon - 2)$ it was found which of the features is mutually linearly dependent [6]. Correlation coefficient r_{ij} can be written

$$r_{ij} = \frac{\Sigma\,(Z_{ij} - \overline{Z_i})(Z_{ij} - \overline{Z_j})}{(\nu = 1) s_{zi} s_{zj}} , \tag{25}$$

Table 1. Research of basic features of operating parameters and wear of combustion engine connecting rod bearings [4]

Tablica 1. Istraživanje osnovnih značajki pogonskih parametara i trošenja ležajeva ojnice kod motora s unutarnjim izgaranjem [4]

Basic feature	**Information system of operational reliability – specification for research**	**Basic feature**	**Information system of operational reliability – specification for research**
Z_1	Combustion engine output (kW / cylinder)	Z_{19}	Bearing bushing, non-stick (cm^2)
Z_2	Engine rotations (s^{-1})	Z_{20}	Non-stick galvanic layer (cm^2)
Z_3	Mileage (Mh)	Z_{21}	Erosive wear (0 – 4)
Z_4	Bushing thickness (mm)	Z_{22}	Plastic deformation of bushing (cm^2)
Z_5	Lining of bearing metal (mm)	Z_{23}	Friction corrosion of external surface (0 – 4)
Z_6	Running-in and operating layer (mm)	Z_{24}	Bushing overlap (mm)
Z_7	Smooth wear of the edge of sliding surface (mm)	Z_{25}	Elastic deformation of upper bushing (mm)
Z_8	Smooth wear of the center of sliding surface (mm)	Z_{26}	Elastic deformation of lower bushing (mm)
Z_9	Galvanic layer (%)	Z_{27}	Mean deviation of bushing bore (mm)
Z_{10}	Stains on sliding surface (%)	Z_{28}	Maximum ovality (mm)
Z_{11}	Abrasive wear (0 – 3)	Z_{29}	Maximum conicity (mm)
Z_{12}	Thermal coloring (0 – 5)	Z_{30}	Vertical bearing clearance (mm)
Z_{13}	Cavitation (%)	Z_{31}	Horizontal bearing clearance (mm)
Z_{14}	Working surface porosity (0 – 2)	Z_{32}	Nominal diameter of stub (mm)
Z_{15}	Face porosity (0 – 2)	Z_{33}	Mean deviation of stub diameter (mm)
Z_{16}	Fatigue cracks, longitudinal (0 – 2)	Z_{34}	Maximum ovality (mm)
Z_{17}	Fatigue cracks, vertical (0 – 2)	Z_{35}	Maximum conicity (mm)
Z_{18}	Fatigue cracks, oblique (0 – 4)		

Table 2. Significance of correlation of individual features

Tablica 2. Značaj korelacije pojedinih značajki

Strength relation (in order)	**Correlated feature**		**Correlation coefficient**	**Determination coefficient**
	Z_i	Z_j	r_{ij}	d_{ij} (%)
1	Z_{12}	Z_9	0,96	92
2	Z_{17}	Z_{12}	0,92	85
3	Z_8	Z_3	0,87	76
4	Z_{23}	Z_{21}	0,81	62
5	Z_{23}	Z_{10}	0,79	58
6 – 7	Z_{17}	Z_9	0,77	59
6 – 7	Z_{18}	Z_{17}	0,75	56
8	Z_{18}	Z_{12}	0,74	55
9	Z_{23}	Z_7	0,71	50
10	Z_7	Z_3	0,69	48
11 – 12	Z_{18}	Z_{10}	0,69	48
11 – 12	Z_{23}	Z_3	0,68	46
13	Z_{17}	Z_{10}	0,67	42
14	Z_{23}	Z_{17}	0,66	44
15	Z_{23}	Z_{18}	0,63	40
16 – 17	Z_{18}	Z_9	0,62	38
16 – 17	Z_{10}	Z_3	0,61	37
18	Z_{20}	Z_{21}	0,59	35
19 – 20	Z_8	Z_7	0,56	31
19 – 20	Z_{11}	Z_9	0,55	30

for $\upsilon = 2(N_{lab} + N_{prov})$ and with an estimate of coefficient of determination

$$d_{ij} = 100 r_{ij}^{2} \quad [\%], \qquad (26)$$

for $i, j = 1, 2, \ldots, 35$; $(-1 \leq r_{ij} \geq -1 \text{ and } 0 \leq d_{ij} \geq 100)$; level of significance $\alpha = 0{,}05$.

4. Conclusion

A further part of research is planned to analyze data by methods of censored selection by time when fatigue tests are specified in instructions, which determine a maximum time of the test at each level of amplitude σ_i. A number N_0, which determines a maximum number of cycles for testing of every sample, is given in advance. According to these instructions, the fatigue life tests can be divided into two groups:

- group A, which will cover all values, e.g. fatigue life that did not reach the value N_0;
- group B, which will cover, e.g. fatigue life, the value of which we do not know, but we know that they exceed the prescribed value N_0;

For an actual given example, cases were analyzed when a time of operation (feature Z_3) is significantly stochastically dependent on further features Z_i. In practice, it was an analysis of features (Z_3, Z_i) for $i = 7, 8, 10, 23$, at which an important correlation dependency was observed, in the following order

$\{Z_3 \leftrightarrow Z_8\}$ … $r_{38} = 0.87$; $d_{38} = 76\ \%$

$\{Z_3 \leftrightarrow Z_7\}$ … $r_{37} = 0.69$; $d_{37} = 48\ \%$

$\{Z_3 \leftrightarrow Z_{23}\}$ … $r_{323} = 0.68$; $d_{323} = 46\ \%$

$\{Z_3 \leftrightarrow Z_{10}\}$ … $r_{310} = 0.61$; $d_{310} = 37\ \%$

for which information ($i = 3, 7, 8, 10, 23$; $\upsilon = 1, 2, \ldots, 28$) that were obtained from information system of operating reliability and diagnostics are the basis for a more detailed creative analysis of failure rate and diagnostics of objects tested. These will be the following close relations:

- Time of operation – smooth wear of the center of sliding surfaces,
- Time of operation – smooth wear of the edges of sliding surfaces,
- Time of operation – friction corrosion of external surfaces,
- Time of operation – stains on sliding surfaces;

The result of research provides important information that enable optimizing the operating diagnostics of objects tested (internal combustion engines) based on five important diagnostic parameters.

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