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# *MANUFACTURING ENGINEERING AND AUTOMATED PROCESSES*

# *МАШИНОБУДУВАННЯ, АВТОМАТИЗАЦІЯ ВИРОБНИЦТВА ТА ПРОЦЕСИ МЕХАНІЧНОЇ ОБРОБКИ*

**UDC 669:621. 02**

## RISK INDICATORS AND DIAGNOSTIC MODELS FOR SUDDEN FAILURES

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***Summary***. *The method of the resource safety index is substanciated. It is used to assess reliability, with both gradual and sudden failures. A model of the periodicity of emissions for mechanical systems of industrial production is developed.*

***Key words***: *statistical reserve, element of the mechanical system, sudden failure, resource safety index, risk.*

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**The statement of the problem.** In order to determine the probability of failure-free operation during sudden failures, the model of "load-strength" comparison is usually used. Reliability is defined as the probability of exceeding the load over strength. The "load-strength" model has been worked out in detail for various combinations of statistical distributions and is a classic approach. As a result this model is also used for failures of a gradual type. But for fatigue failures the conditionally selected limit value of the load can exceed the minimum strength level in many times not reflecting on the actual reliability. And according to the existing model itcan result in a failure. To overcome this contradiction several ways not proved to be effective are offered.

The comparative model "work-resource" distinguishing the resource-based approach is the comprehensive solution to the gradual failures problem. It works fine at the operation stage, when the diagnosis of the residual resource is carried out by controlling the natural parameter which is the operation life The ratio of maximum operation life at the time of control to the minimum resource (which is determined in the statistical aspect by its own distribution functions) forms a guaranteed operation life factor. The logarithm of its current value in the form of the security index decreases linearly with the operating time. When the security index reaches zero value it indicates that the object is used with the unacceptable risk.

The similar use of the risk indicator for sudden type failures is not possible according to the classical model. In general, the model "load - strength" is not adapted for the current control of the technical condition. Therefore, the purpose of the available researches is to use the resource model for sudden failures and develop the algorithm for the safety indexes

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determination. Harmonization of the technical condition estimation methods as the result gives an opportunity to increase the service reliability.

**Approaches to the interpretation of the statistic capacity.** In the theory of reliability the representation of the failure probability is usually proportional to the area of the overlap under the right area of the graph of the density distribution indicator of the acting process that damages, *f(y)* and under the left area of the same graph of the system resistance index *f(Y)*. Therefore the failure probability $Q$ is determined by the statistical reserve $\gamma$ and the Laplace's function $\Phi$ :

$$Q = \Phi(\gamma) \; . \tag{1}$$

For normally distributed independent indices $y$ and $Y$ (for $Y>y$) we have:

$$\gamma = \frac{\bar{Y} - \bar{y}}{\sqrt{S_Y^2 + S_y^2}} \, , \tag{2}$$

where $\bar{Y}$ and $\bar{y}$ , and $S_y$ and are respectively the median values and the mean square deviations (MSD) of $y$ and $Y$ indices.

The statistical reserve in this formulation, referred in the literature as the Cornell's safety index [1], can be interpreted as the minimum distance from the center of O to the line corresponding to the equation $\varepsilon=Y\text{-}y$, separating the safe state from the failure one (fig. 1).

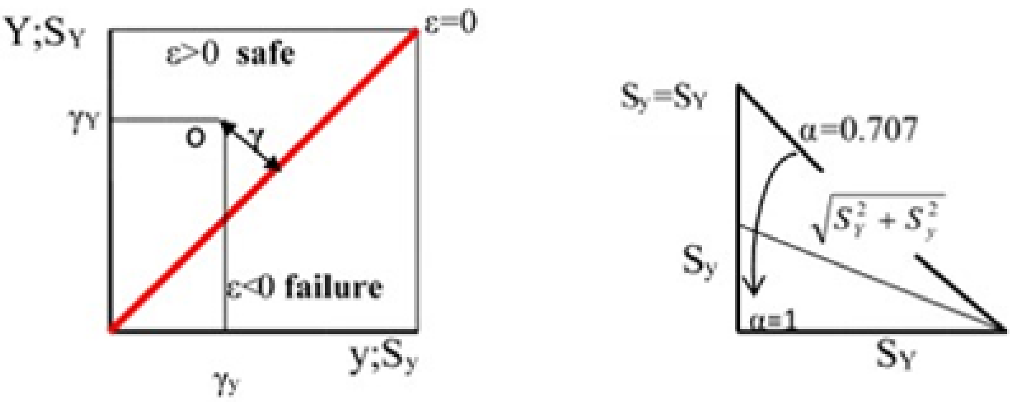


**Figure 1.** Prior to the statistic reserve (right), and the correction of α to the next (left)

The position of the center O is determined by the dimensionless indices of the technical state $\gamma_y = \bar{y}/S_y$ and $\gamma_Y = \bar{Y}/S_Y$ , which are opposite to the variation values coefficients $y$ i $Y$. The denominator of the formula (2) is the MSD of the value ε. The method of statistical reserve (in the technical literature it is called first-orderecond-momentmethod [2, 3]) is developed for multidimensional reliability situation when the object is subjected to multidegradation processes, each of them has the safety index $\gamma_i$ obtained by (2). Then the formula (1) determining the probability of the boundary state *is converted into* $Q=\Sigma\Phi(\gamma_i)$ [4]. This proves the proper use of the rule for summing up the system risks.

The described approach is suitable for sudden failures; for gradual failures it is rather conditional, and for fatigue failure estimation it is ineffective. To calculate of the reliability function of power systems in the case of sudden failures, a method that takes into account the dynamic interaction between the load (parameter $y$) and strength (parameter $Y$) looks promising.

In this case, instead of their fixed values, the time functions are used: $\varepsilon(t) = Y(t) - y(t)$. Due to this, you can get rid of the excessive conservative assessment of reliability inherent in consistently combined structures. But such an analysis looks complicated, despite the fact that it contains only a few primitive data [5].

Providing that the safety index and statistical reserve are the resource interpretations, it is possible to use formula (1) for gradual failures. In this case the probability of failure is represented by comparing the operation life distribution functions. Here the probability of the failure is represented by comparing the operation life $t_P$ and resource $T_P$ distribution functions and in the general case by comparing the parameters $y_P$ and $Y_P$ distribution (Fig. 2). For its determination we use the area of positive quantiles $u_Q$ for the graph $t_P$ and $y_P$ and the area of negative quantiles $-u_Q$ for the graphs $T_P$ and $Y_P$. The probability of a failure in the form of its quantile will correspond to the cross point of these graphs (Fig. 3).

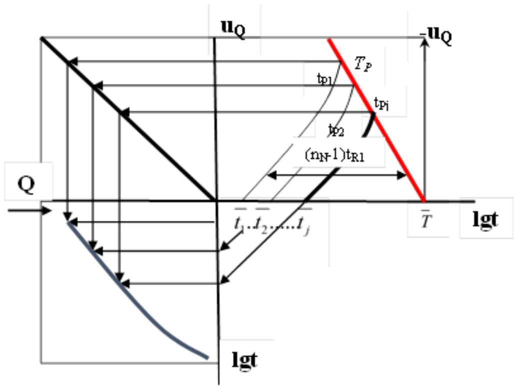


**Figure 2.** Scheme for the formation of the safety index and the function of gradual failures in the lifetime functions of distribution of $T_P$ and operating time $t_p$

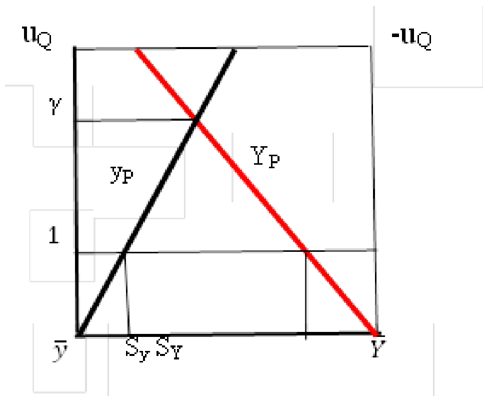


**Figure 3.** To determine the statistical reserve when comparing the distribution functions of the diagnostic parameter

At the same place the safety index $\beta_{\Sigma R}$ equals zero. As the slope of the $t_P$ and $T_P$ graphs is determined by the MSD operation life and the resource $S_t$ and $S_T$, the statistical reserve according to such approach is:

$$\gamma = \frac{\bar{Y} - \bar{y}}{S_Y + S_y}. \tag{3}$$

The given dependence according to its structure is similar to the Cornell safety index, where the normal distribution of the value *lnT* is used [1,4]. The difference between the two approaches for determination of the failure probability is in the fact that comparing the distribution density *f(y)* i *f(Y)* in order to find the value of $\gamma$ by (2) in its denominator the hypotenuse of the rectangular triangle with the catechies in the form of MSD $S_Y$ i $S_y$ (Fig. 1) is used. When comparing the same functions of the technical condition distribution indicators in the denominator (3), the sum of the cathetuses or the MSR $S_Y$ i $S_y$ (fig. 1, right) is substituted. This form is used in the algorithm of the determination of the total strength reserve by the partial reserves of the influence factors [6]. Here the relationship between formulas (2) and (3) is carried out due to the correction function *α(y/Y):*

$$\sqrt{S_y^2 + S_Y^2} = (S_y + S_Y)\cdot\alpha(y/Y). \tag{4}$$

Its value is in the range from 0.707 to 1.0. Providing that $\alpha=0.75$, then with a stock $Y/y=0.25\text{-}4.0$ the difference between the results obtained in (2) and (3) will not exceed 10% [7]. The value $\alpha=0.707$ corresponds to the situation of the equality of the MSD $S_Y = S_y$ (Fig. 1, right). Then the size of the correction can be set depending on the linear form of the function $\alpha(y/Y)$:

$$\alpha = 1 - 0.293\frac{S_y}{S_Y}. \tag{5}$$

Here the ratio of MSD should be more than one. For $(S_y/S_Y) < 1$, we must take in (5) the inverse relation of the MSD $S_Y/S_y$.

Thus, the second approach (the method of the resource safety index $\beta_{\Sigma R}$) is more conservative, contributing to decrease the risk and guaranteed security providing. Such interpretation of the failure probability logically follows from the definition of the security index based on the resource reserve (more precisely the lifetime, since sometimes the resource is understood as a reserve). The described principle of the statistical resource reserve determination is fully proved, because the durability MSD is sufficiently greater than the operation life MSD: $S_T >> S_t$.

**Safety index for sudden failures.** One of the ways to increase reliability is to reduce the share of sudden failures in their total number. In the technical maintenance strategies, due to the active use of technical diagnostic tools, it is possible to detect some of the defects at an early stage, without allowing them to grow into failure. This reduces the number of gradual $N_p$ failures that occur in non-diagnosed objects. In diagnosed systems, the number of gradual failures of $N_{pd}$ depends on the law of defect detecting probability $P_d(t)$: $N_{pd}=N_p(1-P_d(t))$.The overall level of reliability and security increases in proportion to the proportion of gradual failures in their sum with sudden failures.

This concerns the transformation of the sudden type failures into the failure of the gradual type. Such procedure becomes a reality if it is possible to represent the degradation process as a casual one. Then the operation life $t$ can act as the diagnostic parameter, which is very convenient, since it belongs to a range of natural information sources. The value $t$ as the direct diagnostic sign is used to calculate the security index having a complex characteristic of the technical state during gradual failures. Consequently, there is a supposition for the harmonization of generalized parameter $\beta_{\Sigma R}$ obtaining for technical systems.

Using the theory of emissions, it is possible to set periods of the objects inspection if the accidental degradation process does not lead to working ability loss and is only a deregulation factor. The process of mechanical systems loading results in working ability loss both from fatigue (with its control – the failure of the gradual type), and from static destruction at overloading. Actually, overloading is an ejection. The model of their behavior is extremely difficult to trace experimentally, since the occurrence of overload depends on random factors that are not always known. The information on the main (project, staffing) loading process loading is of great help while solving this problem . It refers, first of all, to the effective frequency of the process and the MSD of a normally distributed load (stress) $S_y$ under normal operating conditions (A, Fig. 3). The overload value can be measured by means of the peak factor $\gamma = \bar{y}/S_y$ – a dimensionless value distributed in the projected area of operation by the Rice exponential distribution (B, Fig. 4) [9,8]:

$$P = \exp\left(-\frac{\gamma^2}{2}\right). \tag{6}$$

In the area of emergency extreme operating conditions, the overloads occurrence is subjected to the double exponential distribution (C, Fig. 4) [8]:

$$P = \exp(-\alpha_e \cdot \ln \gamma). \tag{7}$$

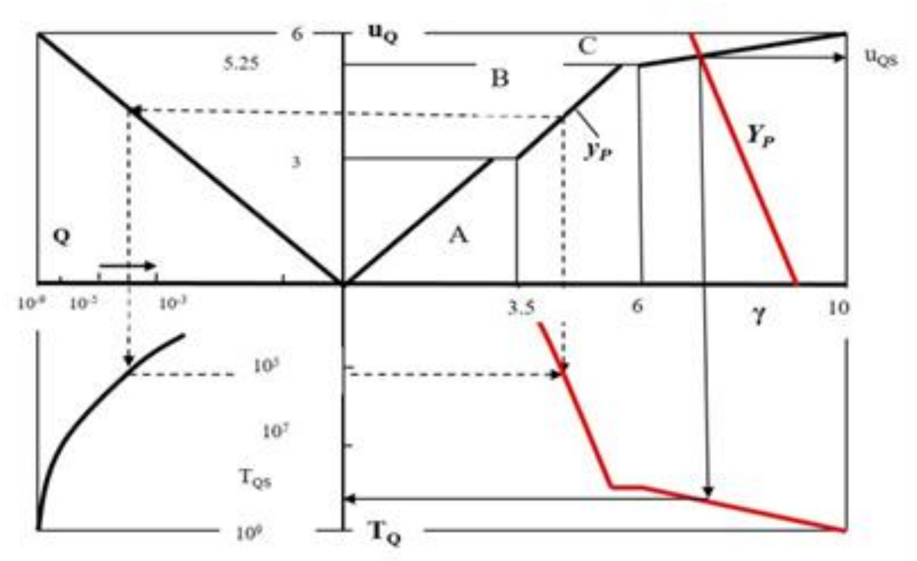


**Figure 4.** The scheme of forming a periodicity diagram $T_Q$ (dashed arrows) and finding the durability with a sudden failures $T_{QS}$ (continuous arrows) in terms of the distribution functions of the parameter $y_P$ and its permissible value $Y_P$

Accepted at the hypothesis level, value $\alpha_e=9$ was proved for the process of loading the pipe rolling mill by means of recording the facts of the safety devices destruction from overloadings. These equations can be approximated in the coordinates of dimensionless indices of normal quantile distribution $u_P$ – the peak factor $\gamma$ by the following way:

$$u_P = -\frac{1}{2} + \gamma \text{ – area B: } 3<u_P\leq 5.25,\ \ 3.5<\gamma\leq 6, \tag{8}$$

$$u_P = \frac{66}{16} + \frac{16}{3}\gamma \text{ – area C: } 5.25<u_P\leq 6,\ \ 6<\gamma\leq 10. \tag{9}$$

The quintile of the failure probability defined by the intersection point of the graphs for the functions of the load and the strength $y_P$ and $Y_P$ distribution for this approximation is as follows:

$$u_Q = \frac{\bar{Y} - \bar{y} - 0{,}5S_y}{S_y + S_Y} \text{ – area B,} \tag{10}$$

$$u_Q = \frac{\bar{Y} - \bar{y} + 22S_y}{5{,}33S_y + S_Y} \text{ – areaь C.} \tag{11}$$

For analytical or machine calculations the relationship of quantile $u_Q$ - the failure $Q$ probability can be can be done by the dependence (*II* quadrant, Fig. 4) [10]:

$$Q = 0.65\exp\left[-0.443\left(0.75 + u_Q\right)^2\right]. \qquad (12)$$

The transition from the parametric-power interpretation of the sudden failure probability to the resource is carried out on the basis that the durability of the single sudden failure (static destruction) of $T_Q$ is inverse to the failure probability Q: *Q:* $\boldsymbol{T_Q=Q^{-1}}$TQ = Q-1 (*III* quadrant, Fig. 4)

Comparing the load and strength $y_P$ и $Y_P$ distribution functions the kinetics of the change in the failure probability in time is also determined (*III* quadrant, Fig. 4). Dependence *Q(lgT)* shows how the risk increases during operation (the more quantil $u_Q$, the less failure $Q$ probability – the scale $Q$ is uneven and increases towards the coordinates origin). The given dependence is analogous to the reliability function. easy to The latter can be obtained in explicit form *P(t)*, taking into account that *P=1-Q*. As a result, we can obtain the emission periodic curve *T(γ)* (*IV* quadrant, Fig. 4), which is an analogue of the fatigue curve. Due to it the durability under the static destruction $T_{QS}$ (solid arrows, Fig. 4) characterizing the position of the safety diagram since $\boldsymbol{\beta_{R0}=lgT_{QS}}$ is determined.

The algorithm for determination of the security resource index for sudden failures is favourably to investigate **the example**. The element of mechanical system is operating under the load followed by periodic overloads. The element is destroyed at the stress $\bar{\sigma}_f = 500MPa$ having the meaning of the resistance median value $\bar{Y}$ . The coefficient of variation of this normally distributed value is assumed to be equal to 10% corresponding to the MSD $S_Y=50MPa$. The periodically-random process of loading is characterized by the average value of the maximum stress cycle $\bar{\sigma}_{\max} = 50MPa$ which in the diagnostic aspect has the meaning of the parameter $\bar{y}$. The variation of the $\sigma_{max}$ index which is also normally distributed is 50%, then the MSD will be $S_y=25MPa$.The effective frequency of the load process is 1 Hz. The strength reserve being equal $n_\sigma = \bar{Y}/\bar{y} = \bar{\sigma}_f/\bar{\sigma}_{\max} = 10$ does not cause any fears, as well as the probability of destruction at full load is defined by formula (2). Taking into account the overloads distribution the destruction probability quantile in (11) will be $u_Q=5.45$. The resulting value is greater than $u_Q=5.25$, that indicates the proper use of this formula for extreme-emergency conditions of operation. The same result will be for all similar combinations $y_P$ and $Y_P$, that is, for all $n_\sigma=10$ and the indicated variations.

The quantile defined in (12) corresponds to the failure probability $Q=2.6\cdot10^{-8}$ being within the limits of acceptable risk. Durability at static fracture is predicted as $T_{QS}=3.8\cdot10^7$*cycles* providing operation life $T_{QS}=10555$*hours*. Then the output security index will be $\beta_{R0}=lg10555=4.02$.

If under severe service (corrosion, cracks) the strength degradation occurs and destructive tensions are reduced to $\bar{\sigma}_f = 300MPa$ but the load level increases up to $\bar{\sigma}_{\max} = 100MPa$ at variation of 20%, then the results of the prediction will change significantly. MSDs become close to each other – $S_y=20MPa$, $S_Y=30MPa$. Therefore it is reasonable to take into account the correction $\alpha=0.75$ derived from (5). Then, for determination of $u_Q$ the formula (10) is used in the following way: $u_Q=(300-100-0.5\cdot 20)/[(20+30)\cdot 0.75]=5.07$. As the result, we have: $Q=3.1\cdot 10^{-7}$, $T_{QS}=400$ *hours* and $\beta_{R0}=2.95$.

**Conclusions.** Thus, the durability estimation due to the overload occurrence is important while extending the long resource equipment life. Units with the limited resource are regularly restored, and the basic elements of mechanical systems are often not paid attention to, which is unwise.

The concept of reliability increase due to the transformation of sudden failures into the gradual failure got its further development. In this aspect, based on the theory of emissions, a resource interpretation of the overloads occurrence in mechanical systems of industrial equipment is offered. This allows us to determine the current value of the security index at single fracture that relates to the given concept.

The principle of the determination of the failure probability by comparing the functions of the resource and operation time distribution which in the combination with the use of the complex diagnostic indicator – the resource security index results in the expression of the statistical reserve in the form of (3) with the addition of the correction function $\alpha(y/Y)$ in the form of (5) is substantiated.

**References**


1. Cornell C.A. A Probability Based Structural Code // ACI-Journal. № 12, Vol. 66. 1969. Pp. 974 – 985.
2. Freudenthal A.M. Safety and the Probability of Structural Failure// Transactions, ASCE. 1956. Vol. 121. Pp. 1337 – 1397.
3. Freudenthal A.M. The Safety of Structures // Transactions, ASCE. 1947. Vol. 112. Pp. 125 – 180.
4. Shinozuka M. Basic analysis of structural safety // Journal of Structural Engineering. 1983. Vol. 109. No, 3. Pp. 721 – 740.
5. Peng Gao and Liyang Xi. Reliability-Based Analytic Models for Fatigue Lifetime Distribution Estimation of Series Mechanical Systems under Random Load considering Strength Degradation Path Dependence // Mathematical Problems in Engineering. Vol. 2017. Article ID 5291086, 15p. https://doi.org/10.1155/2017/5291086.
6. Huther M. Probabilistic and semi- probabilistic format in fatigue ship classification rules / M. Huther, S.Maherault, G.Parmentier, G.Cesarine // Fatigue testing and analysis under variable amplitude loading.- Mayfield, PA: ASTM, 2005. P. 535 – 543.
7. Ravindra M.K., Heaney A.C., Lind N.C. Probabilistic evaluation of safety factors. 1969. 13P. http://www.e-periodica.ch / bse-re-001.1969.4.63/.
8. Bolotin V.V. Forecasting the life of machines and structures. Moscow: Mechanical Engineering, 1984. 312 p. [in Russian].
9. Belodedenko S.V. Assessment of safe durability of structural elements during the design and operation of process equipment / Factory Laboratory. Diagnostics of materials. 2005. № 6. P. 40 – 46 [in Russian].
10. Reliability and Efficiency in Engineering: Reference. In 10 t. M. : Mashinostroenie, 1989. T. 7. Quality and reliability in the production / ed. I.V. Apollonov. 280 p. [in Russian].


**Список використаної літератури**


1. Cornell, C.A. A Probability Based Structural Code // ACI-Journal. –№ 12 – Vol. 66. – 1969. – Pp. 974 – 985.
2. Freudenthal A.M. Safety and the Probability of Structural Failure // Transactions, ASCE. – 1956. – Vol. 121. – Pp. 1337 – 1397.
3. Freudenthal, A.M. The Safety of Structures // Transactions, ASCE. – 1947. – Vol. 112. – Pp. 125 – 180.
4. Shinozuka, M. Basic analysis of structural safety // Journal of Structural Engineering. – 1983. – Vol. 109, No, 3. – Pp. 721 – 740.
5. Peng Gao and Liyang Xi. Reliability-Based Analytic Models for Fatigue Lifetime Distribution Estimation of Series Mechanical Systems under Random Load considering Strength Degradation Path Dependence //

Mathematical Problems in Engineering. – Vol. 2017. – Article ID 5291086, 15 p. – https://doi.org/10.1155/2017/5291086.
6. Huther, M. Probabilistic and semi- probabilistic format in fatigue ship classification rules / M. Huther, S. Maherault, G. Parmentier, G. Cesarine // Fatigue testing and analysis under variable amplitude loading.- Mayfield, PA: ASTM, 2005. – P. 535 – 543.
7. Ravindra, M.K., Heaney A.C., Lind N.C. Probabilistic evaluation of safety factors. – 1969. – 13P. – http://www.e-periodica.ch / bse-re-001.1969.4.63/.
8. Болотин, В.В. Прогнозирование ресурса машин и конструкций [Текст] / В.В. Болотин – М.: Машиностроение, 1984. – 312 с.
9. Белодеденко, С.В. Оценка безопасной долговечности элементов конструкций при проектировании и эксплуатации технологического оборудования [Текст] / С.В. Белодеденко // Заводская лаборатория. Диагностика материалов. – 2005. – № 6. – С. 40 – 46.
10. Надежность и эффективность в технике: справочник. – В 10 т. – М.: Машиностроение, 1989. – Т. 7. Качество и надежность в производстве; под ред. И.В. Аполлонова. – 280 с.

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# ПОКАЗНИКИ РИЗИКУ І ДІАГНОСТИЧНІ МОДЕЛІ ПРИ РАПТОВИХ ВІДМОВАХ

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***Резюме.*** *Обґрунтовано метод ресурсного індексу безпеки. Він використовується для оцінювання надійності як поступових, так і раптових відмов. Розроблено модель періодичності викидів для механічних систем промислового виробництва.*

***Ключові слова:*** *статистичний запас, елемент механічної системи, раптова відмова, ресурс, індекс безпеки, ризик.*

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