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NEVLIUDOV Igor Sh., D. Sc. in Eng., Prof.
Head of the Department of Computer-Integrated Technologies, Automation and Mechatronics[1]
E-mail: igor.nevluidov@nure.ua

ROMASHOV Yurii V., D. Sc. in Eng., Assoc. Prof.
Professor of the Department of Computer-Integrated Technologies, Automation and Mechatronics[1]
Professor of the Department of Applied Mathematics[2]
E-mail: yurii.romashov@nure.ua

[1]Kharkiv National University of Radio Electronics, Kharkiv, Ukraine
[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine

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ESTIMATING OF DURABILITY INDEXES OF STRUCTURAL ELEMENTS BASED ON IDENTIFICATION OF THEIR DETERMINISTIC PROPERTIES

Durability indexes are presented as a consequence of some deterministic properties inherent in the system and (or) their elements, and it is proposed to determine the durability indexes on the basis of analysis of these properties. The most important for estimating the durability are properties related to the lifetime, and the deterministic properties basic for determining the indexes of durability, can be represented by the function of the dependence of the lifetime on the parameter defining the operational conditions. Estimating the durability indexes is reduced to identification of the deterministic properties representing the dependence of the lifetime on the parameter defining the operational conditions. An example of estimating the durability of pipes of superheaters of steam boilers demonstrates the proposed approaches with relatively less complexities. This particular example shows that deterministic properties can have a significant influencing on the durability due to significant differences between the density function of the parameter defining the operational conditions and the density function of the lifetime. The proposed approaches can be recommended for use to estimate the durability indexes of unique technical systems, such as high-power steam boilers and nuclear power reactors, which are usually manufactured in single batches, as well as to estimate the durability indexes of any systems at the stage of their development in order to compare the durability of different constructions.

Keywords: *deterministic properties, identification, durability, computed estimation, mean time to failure, B_x lifetime*

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Introduction. Durability is considered traditionally on the basis of notions about probability, which is in good agreement with a number of engineering systems produced in large amounts, but at the same time it generates significant methodological limitations and contradictions when considering unique systems that are produced in single amounts and have different, in fact, unique modes of operation. The durability is one of principal properties defining the competitiveness of technical systems, and corresponded scientific problems are of current interest at present. For example, the interest to durability problems of gears is due to the newest applications in the jet engines with higher temperatures [1], in the wind generators [2] with extreme loading and low weight requirements. The durability problems are researched now also for traditional thermal [3] and nuclear [4] power plants, for future generations of fusion reactors [5], as well as for green power including solar power plants [6].

It is possible to see that the most studies are based on some common approaches but they are not discussed. The purpose of this article is to show relations of durability indexes and deterministic properties of structural elements, and to reduce durability estimation to identification of principal properties of the structural elements.

Typical durability indexes and main difficulties of their estimating. It is well-known [7] that points of view on the durability are based on the notion about probability. For example, the most widely used durability indexes are as follows [7]:

$$\mathrm{MTTF} = \int_0^\infty t^* f\left(t^*\right) dt^*; \tag{1}$$

$$\int_0^{B_x} f\left(t^*\right) dt^* = \frac{x}{100}, \tag{2}$$

where MTTF (mean time to failure) is the mathematical expectation of the lifetime; B_x is the operating time during which the limiting state (failure) will be achieved with the probability value x in percentile; t^* is the lifetime and $f(t^*)$ is the lifetime's density function.

The notion about the probability supposes the possibility of large number realizations of a researched phenomenon. This is in a good agreement with engineering systems that are made in large amounts. At the same time, such approach has a lot of significant methodological limitations and contradictions for estimating the durability indexes of unique systems which are made in single amounts.

Estimating durability as the result of deterministic properties. The durability indexes are the consequence of some properties inherent to the system or the element and it is naturally to define the durability indexes on the basis of analysis of these properties. To formulate these properties let us consider some parameter ζ defining the operational conditions like temperature, pressure and other similar ones. The lifetime t^* depends on the parameter ζ and this dependence is deterministic. Really, the lifetime is changed exactly corresponding with changing the operating temperature, the pressure. Thus, the principled for the lifetime deterministic properties can be represented by the function:

$$t^* = t^*(\zeta). \tag{3}$$

The natural occurrence of unexpected influences makes it possible to imagine the operational conditions as including the random items so that the parameter ζ can be imagined as the random variable, and the function (3) can be imagined as the function of one random variable. Let us denote $\varphi(\zeta)$ as the density function of the parameter ζ and let us use the result from the theory of probability [8]:

$$f\left(t^*\right)=\varphi\left(\zeta\left(t^*\right)\right)\left|\frac{d\zeta}{dt^*}\right|, \tag{4}$$

where $\zeta = \zeta\left(t^*\right)$ is the inverse to the function (3).

The density function (4) is defined not only by the density function $\varphi(\zeta)$, but also by the deterministic properties (3). Thus, due to the relations (1)–(4) defining the durability indexes is reduced to identification of the deterministic properties represented in the form (3). It is also necessary to have estimations about the density function $\varphi(\zeta)$, but the well-known in the theory of probability density functions can be used. The operational conditions can be defined by the several parameters, but this case is similar to the case (3), (4) in principle and it requires only more complicated mathematical representations of the relation (4). Such approach was used for estimating the durability indexes of heat exchanging pipes in the steam generators of the nuclear power plants considering with the stress corrosion cracking [9].

Example of using the proposed approach. Constructing the function (3) is actually the difficult task and can require solving the complicated mathematical problems [10]. Let us present the example about estimating the durability for the pipes of superheaters of steam boilers showing the proposed approaches with relatively smaller complications. The pipes of the superheater are damaged due to the high-temperature corrosion, and the limiting state of the pipes is defined by decreasing their thickness. Let us use the results from the theory of elasticity [11] and the condition of the pipe's strength:

$$\frac{2p}{1-\rho_1^2}+E\alpha\left(\frac{1}{1-\rho_1^2}+\frac{1}{2\ln\rho_1}\right)\Delta T \le [\sigma], \tag{5}$$

where p = 25 MPa is the internal pressure; ρ_1 is the ratio between the internal and the external radii; E = 160 GPa, $\alpha = 18.5\cdot10^{-6}$ K^{-1} and $[s]$ = 110 MPa are the Young module, the thermal expansion coefficient and the permissible stress of the structural material, respectively; ΔT = 10 K is the difference between the temperatures on the external and internal surfaces.

From the condition (5) we can find:

$$\kappa \le b - a/[\rho_1], \tag{6}$$

where κ is the depth of the corrosive damaging; a = 14 mm and b = 21 mm are the internal and external radii; $[\rho_1]$ is the maximal value satisfying the condition (5).

The dependence of the depth of the corrosive damaging on the time is researched and in the case of burning the fuel oils for example it can be represented as [12]:

$$\lg(\kappa)=2.226-7{,}450/T+\left(1.0+0.234\cdot10^{-3}T\right)\lg t, \tag{7}$$

where T is the operational temperature of the corrosive medium, K; t is the time, h.

Inequation (6) and the relation (7) make it possible to represent the lifetime as follows:

$$\begin{aligned}&\lg\left(b-a/[\rho_1]\right)=\\&=2.226-7{,}450/T+\left(1.0+0.234\cdot10^{-3}T\right)\lg t^*.\end{aligned} \tag{8}$$

Not complicated resolving of the condition (8) makes it possible to find the function (3) analytically so that the parameter ζ will be corresponding to the temperature:

$$\zeta = T. \tag{9}$$

At the same time, it is necessary to have the inverse of function (3), but it cannot be obtained analytically for the function (3) defined through the condition (8). Instead the analytical function defined through the condition (8), it is proposed to use the approximation of this function:

$$t^*(T) = A\cdot T^{-q}, \tag{10}$$

where A and q are the especially defined numerical parameters.

The least square method makes it possible to find the A and q parameters in the approximation (10) for the function defined by the condition (8) so that:

$$q = 18.6056865;\ A = 1.31862\cdot10^{60}\ \text{h}\cdot\text{K}^q. \tag{11}$$

Figure 1 *a* shows that the approximation (10), (11) in a very good agreement with the analytically defined function, but it makes it possible to find the inverse function:

$$T(t^*) = A^{1/q}\cdot(t^*)^{-1/q}. \quad (12)$$

Considering further, the density function of the operational temperature is corresponded to the uniform distribution (see Figure 1 *b*):

$$\varphi(T) = \begin{cases} (T_{\max} - T_{\min})^{-1}, T_{\min} \le T \le T_{\max}, \\ 0, \qquad T_{\max} < T < T_{\min}, \end{cases} \quad (13)$$

where $T_{\min}$ = 813 K and $T_{\max}$ = 933 K are the minimal and maximal possible operational temperatures.

The inverse function (12) and the density function (13) after transformations considering with the relation (9) and the formula (4) will make it possible to have the result:

$$f(t^*) = \begin{cases} (T_{\max} - T_{\min})^{-1} a^{1/q} q^{-1} \cdot (t^*)^{-1-1/q}, \ t^*_{\min} \le t^* \le t^*_{\max}, \\ 0, \qquad t^*_{\min} > t^* > t^*_{\max}, \end{cases} \quad (14)$$

where $t^* = a\cdot(T_{\max})^{-q}$ and $t^*_{\max} = a\cdot(T_{\min})^{-q}$.

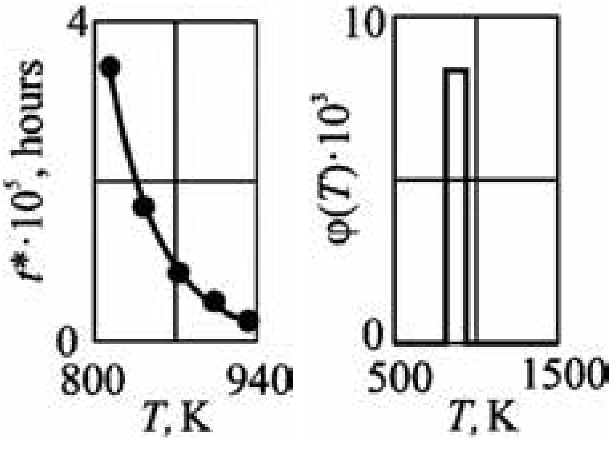
The density function (14) is presented on the Figure 2 *a*. Using the result (14), let us define the durability index (1):

$$\text{MTTF} \cong 116{,}700 \text{ h}. \quad (15)$$

The B_x lifetime (2) is presented on the Figure 2 *b*.

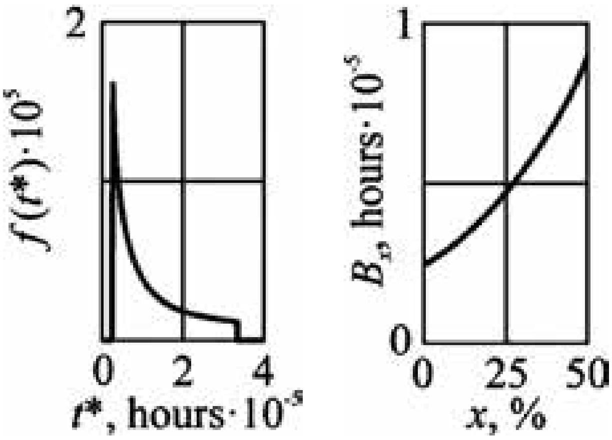
Conclusion. The generalized idea and the technique of using the approaches for estimating the durability indexes on the basis of identification the deterministic properties of the considered systems and (or) their elements are fully presented. Due to this research the following affirmations are substantiated.

The most principal for estimating the durability are the properties about the lifetime, and the principled for the lifetime deterministic properties can be represented by the function of dependence of the lifetime on the parameter defining the operational conditions. Defining the durability indexes is reduced to identification the deterministic properties of dependence of the lifetime on the parameter defining the operational conditions.



a *b*

Figure 1 — Computed points (markers) and approximation (curve) of dependence of the lifetime on the operational temperature (*a*) as well as the density function (*b*) of the operational temperature



a *b*

Figure 2 — Density function of the lifetime (*a*) and the B_x lifetime (*b*)

In the particular example, it is shown that the deterministic properties can have the significant influencing on the durability indexes due to the significant differences between the density function of the parameter defining the operational conditions and the density function of the lifetime.

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И.Ш. НЕВЛЮДОВ, д-р техн. наук, проф.
заведующий кафедрой компьютерно-интегрированных технологий, автоматизации и мехатроники[1]
E-mail: igor.nevluidov@nure.ua

Ю.В. РОМАШОВ, д-р техн. наук, доц.
профессор кафедры компьютерно-интегрированных технологий, автоматизации и мехатроники[1]
профессор кафедры прикладной математики[2]
E-mail: yurii.romashov@nure.ua

[1]Харьковский национальный университет радиоэлектроники, г. Харьков, Украина
[2]Харьковский национальный университет имени В.Н. Каразина, г. Харьков, Украина

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ОЦЕНКА ПОКАЗАТЕЛЕЙ ДОЛГОВЕЧНОСТИ ЭЛЕМЕНТОВ КОНСТРУКЦИЙ НА ОСНОВЕ ИДЕНТИФИКАЦИИ ИХ ДЕТЕРМИНИРОВАННЫХ СВОЙСТВ

Показатели долговечности представляются как следствия некоторых свойств, присущих системе и (или) их элементам. Предложено определять показатели долговечности на основе анализа этих свойств. Наиболее важными для оценки долговечности являются свойства, относящиеся к ресурсу, и основные для определения показателей долговечности детерминированные свойства могут быть представлены функцией зависимости ресурса от параметра, определяющего условия эксплуатации. Определение показателей долговечности сводится к выявлению детерминированных свойств зависимости ресурса от параметра, определяющего условия эксплуатации. Рассмотрен пример оценки долговечности труб пароперегревателей паровых котлов, демонстрирующий предлагаемые подходы с относительно меньшими сложностями. В этом конкретном примере показано, что детерминированные свойства могут иметь значительное влияние на показатели долговечности из-за значительных различий между плотностью распределения параметра, определяющего условия эксплуатации, и плотностью распределения ресурса. Предложенные подходы могут быть рекомендованы к использованию для оценки показателей долговечности уникальных технических систем, таких как паровые котлы большой мощности и ядерные энергетические реакторы, которые обычно изготавливаются единичными партиями, а также для оценки показателей долговечности любых систем на стадии их разработки, чтобы сравнить долговечность различных вариантов конструкции.

Ключевые слова: *детерминированные свойства, идентификация, долговечность, расчетная оценка, средний ресурс, гамма-процентный ресурс*

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