A concept of the predicting of technical state of devices

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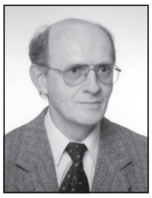
ABSTRACT



The paper presents possibilities and limitations associated with technical state predicting procedure of devices, as well as it indicates the necessity of improving the present scheduling methods of preventive maintenance operations of ship power plant devices. It has been also showed that by making transformation of the wear rate distributions of device elements into the distributions of time of their correct- to-limit-state operation it is possible to predict their technical state and to suitably schedule their maintenance operations.

Keywords : technical state, prediction, maintenance, mathematical transformations, probability distributions

INTRODUCTION

In the process of predicting technical state of a device, in a result of which an optimum prediction containing a date and range of the next testing of the state is formulated, the device's user generates information which makes it possible to control keeping the device in the state of serviceability. An essential element of such control is to know prediction methods of device's state, containing procedures for scheduling a date and range of the next testing and the possible scope of overhaul operations resulting from it.

Due to a complexity of ship devices, their profitability and operational safety, the preventive maintenance strategy realized on the basis of their wear value is the most important. In order to elaborate such strategy it is necessary to choose an appropriate strategy for predicting working time resources of a given object with taking into account its service conditions [9,11].

When analyzing prediction methods it is not possible to unambiguously show a greater suitability of any of them against other ones because it depends on which kind of objects is subjected to predicting investigations [1,6].

In the present phase of knowledge and practical experience dealing with predicting problems in diagnostics, it is today hard to select an algorithmic procedure which would contain clear-cut recommendations and would exactly precise which methods have to be used for elaborating an optimum prediction in given conditions. Experience shows that in very many situations there is no general method which could be applied as a rule in realizing the process of choosing right diagnostic predictions.

If the ageing of the object is considered as a set of results of actions of processes limiting its service effectiveness, a question arises if it is possible to predict amount of wear of a repairable object and to assess cost-effectiveness of its further using without its replacement or carrying-out its major repair.

For this reason the attempt to present possibilities and limitations which concern the predicting of technical state of devices, as well as to indicate a necessity of improving the current methods of planning preventive maintenance operations of ship power plant devices, has been undertaken.

One of the possibilities may be to elaborate models of failure predicting and scheduling maintenance operations, in which wear phenomena of device elements would be accounted for. A way of transforming the wear rate distributions of device elements into the distributions of time of their correct-to-limit-state operation, was demonstrated. It makes it possible to estimate service life indices for devices, e.g. their working time resources, and to schedule their maintenance operations appropriately.

POSSIBILITES AND LIMITATIONS OF THE PREDICTING OF STATE OF DEVICES

Physical ageing of devices usually occurs due to destructive processes taking place in them, associated with friction, corrosion, errosion, cavitation and fatigue of structural materials of their elements. Along with time of their operation it leads to often and often occurring failures and in consequence to lowering their reliability.

Service reliability investigations are aimed at determination of reliability function of an object, changeable with time of its operation, on the basis of data obtained in service.

Any decrease of reliability level cannot exceed a permissible value, hence it should be assumed that if such event happens the object in question will be taken out of service.

Below has been undertaken an attempt to present some essential possibilities and limitations associated with the predicting of reliability of devices , in order to show that searching for new predicting methods is necessary.

The irreversible wear processes occurring in devices in service cause a monotonically changeable trend of values of diagnostic control parameters to occur.

A basic condition to succeed in predicting the state of devices is to assume a uniform wear rate of their elements, i.e. that a trend of measured quantities is known (failure rate - in case of reliability considerations).

Changes of values of diagnostic parameters obtained from particular state investigations may differ seriously, and their probability density functions are usually not known.

Therfore it can be assumed that :

- the scheduling of the successive diagnostic test of a device is possible as a result of the technical state prediction which consists in determination of future changes of diagnostic parameters and in comparison their instantaneous values with those limiting [12,13,15]
- assessment of a trend depends on all observations of a variable, but a weight attributed to relevant realizations decreases in function of the time passing from the instant of observation up to now. It means that the longer time ago an event has occurred the smaller the weight, and that its importance decreases with the time passing from the instant of occurence of the event [5].

The main tasks for realization of the so described prediction process are the following :

- selection of optimum diagnostic parameters describing a current state and its change during operation of a device
- determination of a predicted value of a diagnostic parameter behind the time horizon of the diagnosis, by using an optimum diagnostic method
- scheduling the time of the sucessive diagnostic test.

When considering the real operation processes one has to do with both deterministic and random processes. The random processes cause that [8] :

- to formally describe phenomena is not possible or very complicated
- the considered phenomena are non-measurable, by convention
- the considered objects and phenomena are subject to continuous changes.

For this reason the following components appear in description of the real processes which occur during operation of a device :

- deterministic ones – possible to be calculated by using inductive methods
- stochastic ones – possible to be determined by using deductive methods on the basis of statistical data,
- or not being a basis for any predictions.

The reliability theory contains only a few theoretical models whose application makes it possible to obtain an exact description of influence of different factors on reliability characteristics of technical objects; therefore further elaborating and testing the mathematical models for reliability investigations of such objects, is justified.

However in any case an empirical mathematical model is simplified and it belongs to an a priori determined class. Usability and properties of some mathematical models important for reliability investigations of ship equipment are presented in [6]. In the case of ship equipment traditional methods for verification of statistical hypotheses by means of tests may be not sufficient to select the most suitable model. Knowledge of a kind of device failure (e.g. sudden or progressive) can facilitate the selecting of an appropriate mathematical model [6,17].

The systems for reliability prediction of objects, described in the subject-matter literature and used in practice, are based on investigations of influence of many factors which determine failure rate analytically described in an empirical model. Accuracy of such models and credibility of reliability predictions resulting from them, depends mainly on accuracy of empirical data obtained from laboratory tests or service investigations.

Wear phenomena in object elements are very complex and many factors influence their course therefore to take all of them into account is impossible; hence to make choice of an optimum set of diagnostic parameters is difficult.

Predicting the technical state of machines on the basis of values of diagnostic parameters changeable in service and related to a longer time period, is associated with a risk that the predicting diagnosis would be based on an out-of-date model, i.e. that whose elements (an optimum set of diagnostic parameters and an optimum prediction method) do not reflect real relationships between the technical state of the system and the predicting diagnosis, any longer . Hence the optimum predicting diagnosis should be stable within the entire period of state predicting. If it appears unstable then it may be applied to a dynamical operation system of machines. Otherwise should be made a decision to modify assumptions and limitations, e.g. by deliberate not-accounting for factors causing unstability and decreasing versatility of the obtained solution.

If in a performed predicting action the statistical information required for the used model is unavailable then it becomes necessary to apply a testing procedure which makes it possible to test in conditions of incomplete data. It is usually associated with the necessity to limit the range of predicting analysis to a short-range horizon.

Diagnostic prediction not always provides results expected from the point of view of its rightness and accuracy. The prediction rightness can be determined by probability of fulfilment of the prediction. The more fully and objectively are parametrized realization conditions of a process the greater the prediction rightness.

In the context of the presented possibilities and limitations it is necessary to search for ways to improve current methods of planning. One of them can be to elaborate such models in which wear phenomena of the object's elements would be taken into account. To this end may serve the transformation of the wear rate distributions of device elements into the distributions of their correct-to-limit-state operation, which would make predicting their technical state and appropriate scheduling their maintenance operations, possible.

TRANSFORMATION OF THE WEAR RATE DISTRIBUTION MODELS INTO THE MODELS OF TIME OF CORRECT--TO-LIMIT-STATE OPERATION OF DEVICE ELEMENTS

To assess service life of devices at the initial stage of their operation is only possible by analyzing their wear processes, to this end failure predicting models accounting for wear phenomena of device elements, are the most suitable [14].

The reliability model of element's wear can be presented in the following form [14] :

$$\int_0^t f_1(t_s)dt_s = \int_{z_g}^{\infty} f_2(z)dz \qquad t \ge 0 \qquad (1)$$

where :

$f_1(t_s)$ – density function of the serviceability time T, for : $0 \le t_s \le t$

$f_2(z)$ – density function of the wear *z* for the fixed value $t \ge 0$

t_s – current duration time of the process of the wear *z*.

The formula (1) expresses equality of the probability of the event consisting in that in the instant *t* or earlier a failure of the object occurred, and the probability that in the instant *t* the object attained the wear value z_g or greater. The relationship (1) is illustrated in Fig.1 [14].

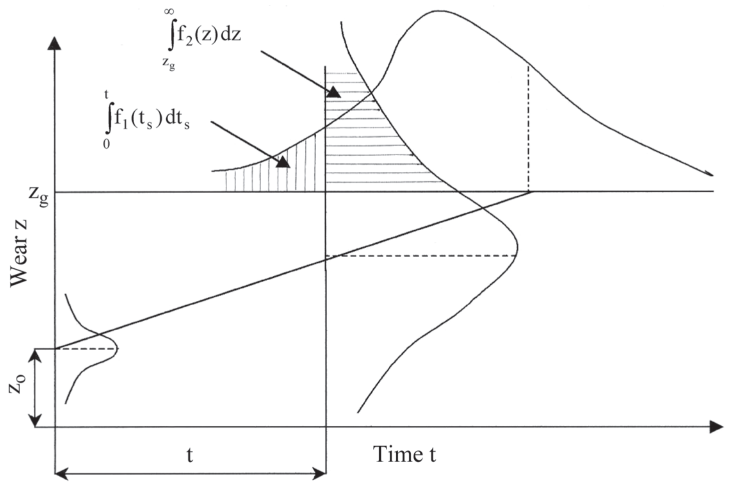


Fig.1. *Schematic diagram of service life assessment on the basis of wear value taken as a random variable*

Making use of the equality (1) one can perform service life assessment by determining the density function $f_1(t)$ on the basis of distribution characteristics of the wear described by the function $f_2(z)$.

If the function $f_2(z)$ for the instant *t* is determined on the basis of observations of changes of wear distribution parameters, performed in the instants earlier than *t*, then by applying the equality (1) one can predict object's service life. To perform such prediction it is necessary to know the allowable wear value z_g and stochastic model of wear process (see [14]).

A wear rate analysis of elements of ship devices shows that their distributions can be approximated by some theoretical distributions : normal, Rayleigh's and Weibull's one. The two-parameter Weibull distribution is the most versatile. In some special cases the exponential distribution can be also applied [2,4,6,7,15].

The wear rate distribution empirically or theoretically determined can be transformed into the distribution of time of correct-to-limit-state operation. By assuming that the wear rate distribution g(u) was obtained for the sufficiently large set of n_o monomial elements, the number of elements n(T) which reached the limit state within the time t = T can be determined by means of the following equation :

$$n(T) = n_o \cdot F(T) \tag{2}$$

If $G(u) = P(U_g < u)$ is the cumulative distribution function of wear rate, and g(u) its density, then the unreliability function F(t) can be expressed as follows [2,3] :

$$\begin{aligned} F(t) = P(T < t) &= P\left(\frac{z_g}{U_g} < t\right) = \\ &= P\left(U_g > \frac{z_g}{t}\right) = \int_{z_g/t}^{\infty} g(u)\,du \end{aligned} \tag{3}$$

Hence :

$$R(t) = 1 - F(t) = \int_{-\infty}^{z_g/t} g(u)\,du \tag{4}$$

Tab.1 presents the solutions of the equation (3) for the density functions of wear rate g(u) according to the normal, Rayleigh, Weibull and exponential distributions.

Tab.1. *Transformation of wear rate distributions into the distributions of time to correct- to-limit-state operation*

Wear rate distributions of elements			Distributions of time to correct- to-limit-state operation		
Distribution	Parameters	Distribution density function g(u)	Probability of reaching the limit state, F(t)	Failure rate $\lambda(t) = \frac{f(t)}{1-F(t)}$	Probability density function $f(t) = \frac{dF(t)}{dt}$
Normal	$\bar{u}$ σ	$\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(u-\bar{u})^2}{2\sigma^2}\right]$	$1 - F\left(\frac{z_g - \bar{u}t}{\sigma t}\right)$	$\frac{\frac{z_g}{\sigma t^2\sqrt{2\pi}}\exp\left\{-\left[\frac{1}{2}\left(\frac{z_g-\bar{u}t}{\sigma t}\right)^2\right]\right\}}{F\left(\frac{z_g-\bar{u}t}{\sigma t}\right)}$	$\frac{z_g}{\sigma t^2\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{z_g-\bar{u}t}{\sigma t}\right)^2\right]$
Rayleigh's	c	$\frac{u}{c^2}\exp\left[-\frac{u^2}{2c^2}\right]$	$\exp\left[-\frac{1}{2}\left(\frac{z_g}{ct}\right)^2\right]$	$\left(\frac{z_g}{c}\right)^2 t^{-3}\left[\exp\left(\frac{1}{2}\cdot\frac{z_g}{ct}\right)^2 - 1\right]^{-1}$	$\left(\frac{z_g}{c}\right)^2 t^{-3}\exp\left[-\frac{1}{2}\left(\frac{z_g}{ct}\right)^2\right]$
Weibull's	a k	$\frac{k}{a}\left(\frac{u}{a}\right)^{k-1}\exp\left[-\left(\frac{u}{a}\right)^k\right]$	$\exp\left[-\left(\frac{z_g}{at}\right)^k\right]$	$\frac{\left(\frac{z_g}{a}\right)^k kt^{-(k+1)}}{\left[\exp\left(\frac{z_g}{at}\right)^k\right]-1}$	$\left(\frac{z_g}{a}\right)^k kt^{-(k+1)}\exp\left[-\left(\frac{z_g}{at}\right)^k\right]$
Exponential	λ = const	$\lambda\exp[-\lambda u]$	$\exp\left[\frac{-z_g\lambda}{t}\right]$	$z_g\lambda t^{-2}\left[\exp\left(\frac{z_g\lambda}{t}\right)-1\right]^{-1}$	$z_g\lambda t^{-2}\exp\left(-\frac{z_g\lambda}{t}\right)$

For instance the way of transforming the density function of wear rate g(u) according to Weibull distribution is the following [2,3] :

$$F(t)=\int_{z_g/t}^{\infty} g(u)du=\int_{z_g/t}^{\infty}\frac{k}{a}\left(\frac{u}{a}\right)^{k-1}\exp\left[-\left(\frac{u}{a}\right)^{k}\right]du= \tag{5}$$

$$=-\exp\left[-\frac{u}{a}\right]^{k}\Big|_{z_g/t}^{\infty}=\exp\left[-\left(\frac{z_g}{at}\right)^{k}\right]$$

Making use of the relationships :

$$f(t)=\frac{dF(t)}{dt} \tag{6}$$

and :

$$\lambda(t)=\frac{f(t)}{1-F(t)} \tag{7}$$

one obtained the expressions for the distribution density function of time to correct-to-limit-state operation, f(t), and the failure rate function λ(t), presented in Tab.1. This way the wear rate distributions were transformed into the distributions of time to correct-to-limit-state operation of elements. The parameters of the wear rate distributions and the allowable limit wear value of element, z_g , become the parameters of the new distributions.

If the parameter W :

$$W=\frac{z_g}{\bar{u}} \tag{8}$$

is introduced and the expressions for the expected wear rate values $\bar{u}$ for particular distributions are assumed, the following forms of the function f(t) are obtained :

for normal distribution of wear rate,

$$\text{where : } z_g=W\cdot\bar{u} \tag{9}$$

$$f(t)=\frac{W\cdot\bar{u}}{\sqrt{2\pi}\,\sigma t^{2}}\exp\left[-\frac{\bar{u}}{2}\left(\frac{W-t}{\sigma t}\right)^{2}\right] \tag{10}$$

for exponential distribution,

$$\text{where : } z_g=W\cdot\bar{u}\qquad \bar{u}=\lambda^{-1} \tag{11}$$

$$f(t)=\frac{W}{t^{2}}\exp\left(-\frac{W}{t}\right) \tag{12}$$

for Rayleigh's distribution,

$$\text{where : } \bar{u}=\sqrt{\frac{\pi c^{2}}{2}} \tag{13}$$

$$f(t)=\frac{\pi}{2}\frac{W^{2}}{t^{3}}\exp\left[-\frac{\pi}{4}\left(\frac{W}{t}\right)^{2}\right] \tag{14}$$

for Weibull's distribution,

$$\text{where : } \bar{u}=a\cdot\Gamma\left(\frac{1}{k}+1\right) \tag{15}$$

$$f(t)=\frac{kW^{k}\Gamma^{k}\left(\frac{1}{k}+1\right)}{t^{k+1}}\exp\left\{-\left[\frac{W}{t}\Gamma\left(\frac{1}{k}+1\right)\right]^{k}\right\} \tag{16}$$

Because the Weibull's distribution is the most versatile, the equation (16) may be taken as the general form of f(t) which – for selected values of the parameter *k* – yields particular solutions.

Hence :

- for the parameter value k = 1 the equation (16) is transformed into the equation (12)
- for k=2 the equation (14) is obtained.

The equation (16) is the probability density function f(t) for the two-parameter (W, k) distribution of time of correct-to--limit-state operation , shortly called the W distribution [2].

In this case the reliability function R(t) which expresses the probability that a device will not reach its limit state, can be represented as follows :

$$R(t)=1-\int_{0}^{t}f(t)dt=1-\exp\left\{-\left[\frac{W\Gamma\left(\frac{1}{k}+1\right)}{t}\right]^{k}\right\} \tag{17}$$

The function R(t) may be used to determine, a.o., γ-percent resources of working time of devices, hence for scheduling their maintenance operations. A good conformity of the course of the function R(t) and results of statistical investigations on diesel engine cylinder liners is shown in [3]. Therefore, depending on information at one's disposal, service data or theoretical relationships can be used for assessing the process of running down the working time resources of device elements.

ASSESSING THE PROCESS OF RUNNING DOWN THE WORKING TIME RESOURCES OF DEVICE ELEMENTS

Working time of a device, after which its working time resource is exhausted, can be determined on the basis of the working time resource specified by the device's producer or that determined with the use of statistical data obtained from service.

A course of running down the working time resource of any device element is exemplified in Fig.2, at accounting for the following assumptions [11] :

- the worn-out element (that of exhausted time resource) is replaced with a new one
- at the beginning of the service process or just after replacement of an element the ratio of the working time resource t_j and the time resource t_n (specified by the device's producer) equals 1, and it equals 0 when the working time resource is run out, i.e the limit state is attained
- the running-down process of working time resource of an element in service, is linear.

The diagram shown in Fig.2 presents the way of determining the time after which an element is to be replaced with a new one or subjected to major repair.

In the course of operation one does not usually let the limit state of device elements to occur, therefore their replacement is made in advance. In Fig.2 such procedure is represented by dotted lines. Technical state of an entirely used up (worn out) element of the device whose values of control parameters are contained within the interval between allowable and limit ones [2], is so low that further use of the device in which such element is installed is associated with greater and greater expenditures. Hence the in-advance replacement of an element with a new one as a matter of fact shortens its working time, however it also makes it possible to restore the demanded technical state of the device and to reduce its operational cost.

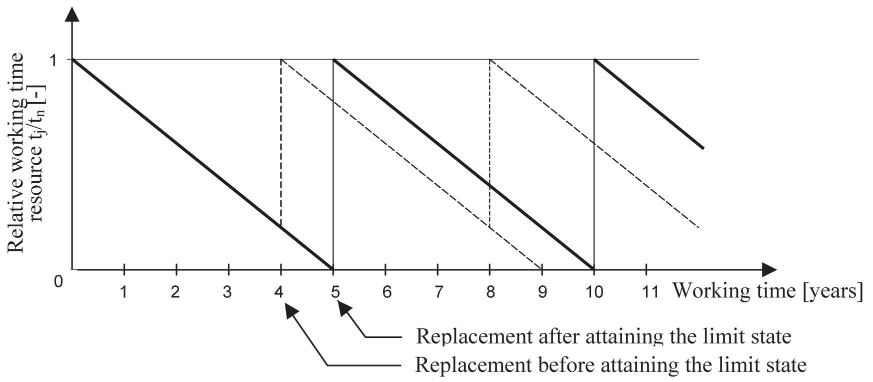


Fig.2. Running-down process of working time resource of an object

In the case of replacement of the entire device with a new one the system (e.g. power plant) in which it has been installed, becomes restored , however if only one of its elements is replaced then the device (or power plant) becomes restored partly. Therefore it can be assumed that in the first case the device's technical state and working time resource become restored to their maximum values, whereas if the object is subjected to overhaul its technical state and working time resource can be maintained at a given level or restored , however they will no longer reach their initial values (those at the beginning of the device's use) and the device in question will be no longer considered as „ a new one". It means that in the case of repaired objects the line of the maximum relative working time resource shown in Fig. 2 will monotonically descend. The entire problem in question is presented a.o. in [12].

By applying the way of the determining of working time resource, presented in Fig. 2, great advantages are obtained by means of analysis of running-down process of working time resources of elements of complex technical objects, e.g. diesel engine, in order to answer the question : **which the engine's elements require to be serviced, and after which time of operation (see Fig.3)**. Similar analysis can be performed for e.g. ship power plant. As a result of it specification of the objects which require maintenance operations in particular years of ship service would be obtained.

Various possible schedules of servicing can be assumed, e.g. after every voyage, each year etc; in each case the scope, time and cost of servicing will be different. It will also depend on service conditions of particular objects, which greatly influence working time resources of the objects.

For instance, Fig.4 presents the way of determining the resources of working time to preventive maintenance, routine repair and major repair, counted from a given service year t_A , at different service conditions.

In the example shown in Fig.4 the object's serviceability time was divided into equal intervals in such a way that the

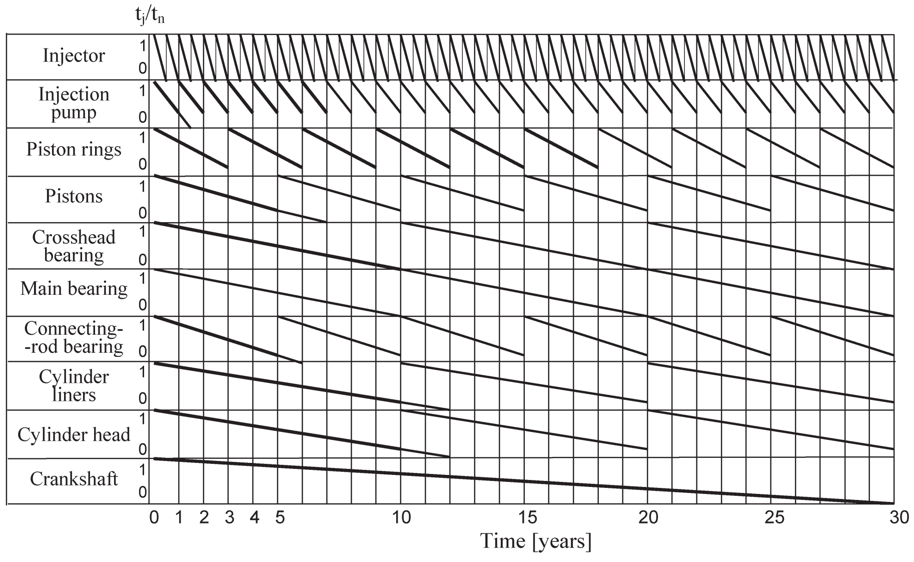


Fig.3. Running-down process of working time resources of combustion engine elements (an example)

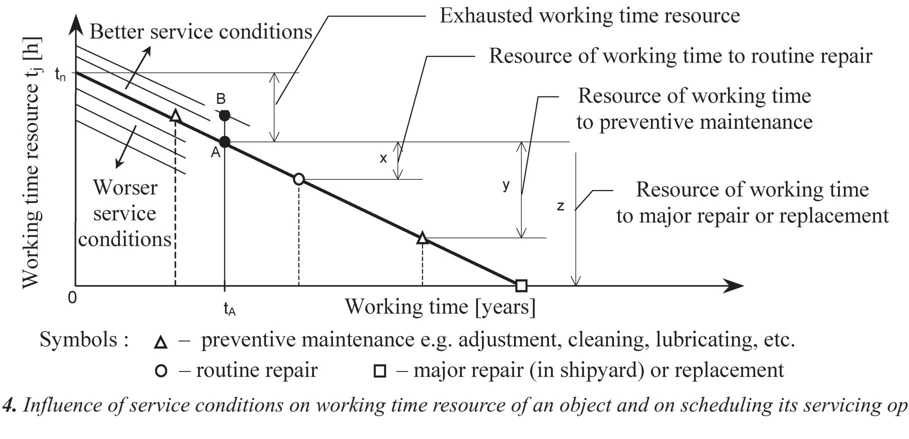


Fig.4. Influence of service conditions on working time resource of an object and on scheduling its servicing operations

time intervals to preventive maintenance, routine repair and major repair were equal (usually given by device producers or shipowner). Any change of service conditions would result in changing the working time resource of the device in question , manifested by shifting-up the line of running-down the working time resource of the device, shown in Fig.4.

For instance, an improvment of service conditions stands for the passing from the point A to the point B and for an appropriate increase of the distances x, y and z determined relative to a new line of running-down the working time resource. As a result it would be necessary to modify the initial schedule of servicing the device.

FINAL REMARKS

- In the subject-matter literature there are no established procedures for the determining of working time resources of technical objects in changeable service conditions.
- The presented concept of the predicting of working time resources may facilitate the scheduling of preventive maintenance of objects and the choosing of optimum servicing plan.
- Usefulness of a given prediction method increases if a comprehensive physical analysis of development of wear processes and their features are performed in advance.

For all prediction realizations it is important to know history of development of the to-be-predicted process. Moreover, an analysis of the conditions which determined past course of the process, assessment of significance of structural components influencing its course, as well as estimation of possible influences in the future, is also important.

- Wear rate distributions of device elements can be used for determining distributions of their working time to limit state and in consequence to determine service life indices characterizing the devices e.g. their working time resources.
- From theoretical and practical point of view the presented distribution W can be useful in describing progressive failures.

NOMENCLATURE

a – scale parameter of Weibull distribution
f(t) – probability density function of time to limit state (time to failure)
F(t) – failure probability function (unreliability function), cummulative distribution function of serviceability time
g(u) – wear rate probability density function
h(z) – wear-out probability density function
k – shape parameter of Weibull distribution
n_o – number of objects in question
n(t) – number of objects failed to the instant *t*
R(t) – reliability function
t – time
t_γ – time of correct operation of object at γ-percent probability (γ-percent time resource)
T – time to limit state (random variable)
u – wear rate (realization); $u = z/t$
u_g – limit wear rate; $u_g = z_g/t$
$\overline{u}$ – expected wear rate value
U – wear rate (random variable); $U = Z/t$
U_g – limit wear rate (random variable); $U_g = z_g/T$
W – expected service life value; $W = z_g/\overline{u}$
z – wear (realization); increment of control parameter value
z_d – initial (lower) wear value
z_g – limit (upper) wear value
Z – wear (random value)
λ – failure rate, exponential distribution parameter
λ(t) – failure rate function
σ – normal distribution parameter; standard deviation.

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