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# Dependability of objects with non-stationary failure rate

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**Abstract.** *Among the diversity and various degrees of significance of the factors that affect an object's failure flow, there is one, i.e. its "ageing," that causes changes in the number of failures per time unit that makes it non-stationary (in terms of dependability). In this context, the elaboration of service procedures is of high importance, especially with regards to long life-cycle objects.* **Methods** *of identifying dependability indicators of stationary objects are known and widely used in practice. Nevertheless, as regards non-stationary objects there are practically no generally accepted approaches to the identification of their dependability indicators that would be convenient for engineering calculations. Meanwhile, the analysis of publications dedicated to this subject given in this paper shows the relevance and potential demand for such methods in various technical matters.* **The aim** *of this paper is in the development of an analytical model of evaluation of dependability indicators of non-stationary objects. The main concept of the proposed approach consists in substituting the real non-stationary object with a virtual analogue, of which the failure flow is stationary, i.e. a formal stationarization (in terms of dependability) of the object occurs, which legitimizes the use of well-developed methods of solving stationary tasks by extending them to the cases of non-stationary objects. The approach is rough. The main problem is identifying the value of the constant failure flow rate of the fake object expressed through the time-dependent parameters of the "ageing" characteristic of the real (non-stationary) object that in this paper is deemed to be known. In order to increase the generality of consideration, the definition of equivalent failure rate (or associated mean time to failure) in this paper is given for three cases: 1) The real object "ages", i.e. its failure rate is an increasing function of time. Two approaches are suggested to the identification of the equivalent failure rate: a) based on the condition of equality of the mean times to failure of both objects (real and fake); b) based on the condition of equality of the dependability functions of the objects to the predefined prediction time. For some laws of "ageing" the task has been solved analytically in closed form. Using the numerical example, the comparative accuracy of the approaches has been evaluated. 2) The object is characterized by a piecewise constant failure rate that is typical to systems and devices that operate in "open" environments (with seasonal changes in failure rate). Both exact and approximate (in linear approximation) expressions for the dependability function and mean time to failure for such object have been obtained. 3) The object's failure rate dependance is a piecewise constant non-periodical time function. Such model is sufficiently universal as after time discretization and piecewise constant approximation with a given accuracy many analytical time dependencies of failure rate can be reduced to it. Method-wise, the task is solved similarly to item 2), i.e. the non-periodic process is treated as a periodic one with an infinitely long period. Under the condition of reasonable practicality of object operation (e.g. for economic reasons) defined in this paper, expressions for the dependability function and mean time to failure have been obtained. The findings of the paper may be useful in solving the dependability-related tasks for non-stationary technical objects.*

**Keywords:** *dependability; failure flow; non-stationarity; periodicity of object states.*

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Dependability indicators, i.e. probability of no-failure over a given time period $p(t)$ and mean time to failure $\overline{t}$ are a significant criterion of a system's (object's) operation [1]. The failure rate $\lambda(t)$ is the input information for the identification of those indicators. Thus, if $\lambda(t)$ is known

$$p(t) = \exp\left[-\int_0^t \lambda(t)dt\right] \quad (1)$$

and

$$\overline{t} = \int_0^\infty p(t)dt. \quad (2)$$

Most existing engineering methods of calculating an object's dependability indicators are based on the hypothesis of its stationarity [1-4], i.e. assume that the rate of failure flow $\lambda(t)$ does not change in time ($\lambda(t)=\lambda_0=const$). In this case formulas (1) and (2) transform as follows:

$$p(t) = \exp(-\lambda_0 t); \quad (3)$$

$$\overline{t} = 1/\lambda_0. \quad (4)$$

Among the diversity and various degrees of significance of the factors that affect an object's failure flow there is one, i.e. its "ageing", that causes an increase of the number of failures per unit time. This circumstance cannot be ignored in cases of long-term operation of an object: $\lambda$ stops being constant and becomes an increasing function of time $\lambda(t)$, while the object essentially passes into the non-stationary ("ageing") class. In this context, the elaboration of service procedures is of utmost importance, especially with regards to long lifecycle objects. That is supported by the publications that appeared over the past few years and that contain dependability evaluations of such socially significant facilities as water resource utilization systems of major cities [5], nuclear power plants [6], structures made of composite materials [7], etc.

A number of systems (facilities) operate in periodically changing conditions. In particular, waste water channel systems typically display a dependance between the failure rate and the operating season; for power supply systems the load is a function of different periods of the day. Therefore, in this case the failure rate changes during the day. Rolling stock of various transportation systems, main underground pipelines operate in periodically changing conditions.

In principle, the solution of any dependability-related task for a non-stationary object is algorithmically identical to a similar task for stationary objects. The difficulties though consist in the fact that calculations involve certain mathematical operations (e.g. integration) that cannot be performed in primitive functions. In such cases the applied dependability theory has to allow some simplifying assumptions in order to achieve the desired result. Those assumptions allow obtaining a solution in a rough analytical form that is convenient for subsequent analysis. Such assumptions can be conventionally grouped into several types. Judging by the latest publications [8-11], we can acknowledge the existence of a distinct type of assumptions that involves substituting the failure flow of a real non-stationary object with a fake one that in some respect is equivalent to the initial one and is convenient for solving the specific task at hand.

This paper sets forth the methods of dependability indicators calculation for objects with non-stationary failure flow. It examines "ageing" objects, of which the rate of failure flow $\lambda$ increases in time, objects with periodic piecewise constant failure rate, objects, of which the failure rate can be represented with a non-periodic piecewise constant function. The last case is sufficiently general, as initially the results of statistical failure data processing is conveniently represented in the above form. Additionally, analytically, after discretization, the given function $\lambda(t)$ can always be represented with a given accuracy with a piecewise constant function of time.

For ageing objects, of which the failure rate increases in time, the main concept of the method consists in substituting the real non-stationary object with a virtual fake analogue, of which the failure flow is stationary and is characterized by a certain constant rate $\lambda_c$. Thus, a formal stationarization of the object occurs, which legitimizes the use of well-developed methods of solving stationary dependability-related tasks by extending them to the cases of non-stationary objects. The value $\lambda_c$ must be "associated" with the parameters of the "law of ageing" of the real object $\lambda(t)$ and be defined by certain additional considerations.

Let us examine two possible approaches to the definition of $\lambda_c$ for ageing objects.

***Approach 1***. In accordance with this approach it is suggested to find $\lambda_c$ out of condition $\overline{t_c} = \overline{t}$, where $\overline{t_c}$ is the mean time to failure of the equivalent ageing object, while $\overline{t}$ is the one of the real ageing object. If $\overline{t}$ is expressed through parameters $\lambda_0$, $\alpha$, $\beta$… of the ageing characteristic, then subject to (4) out of this equation we immediately obtain:

$$\lambda_c = \frac{1}{\overline{t}(\lambda_0, \alpha, \beta...)}. \quad (5)$$

In order to demonstrate the use of this approach let us examine a non-stationary object, of which the failure rate changes in time according to law:

$$\lambda(t) = \lambda_0 + \alpha t, \quad (6)$$

where $\lambda_0$ is the initial failure rate; $\alpha$ is the object's ageing factor ($\alpha>0$).

For this case in [12], the accurate value of mean time to failure $\overline{t}$ is obtained that is expressed through the parameters of the law of ageing (6):

$$\overline{t}(\lambda_0, \alpha) = \sqrt{\frac{2}{\alpha}} \cdot e^{\frac{\lambda_0^2}{2\alpha}} \cdot \frac{\sqrt{\pi}}{2} \cdot \left[1 - \Phi\left(\frac{\lambda_0}{\sqrt{2\alpha}}\right)\right], \quad (7)$$

where $\Phi(\ )$ is the probability integral.

By substituting this expression into (5), for the failure rate of the fake stationary object $\lambda_c$ we obtain:

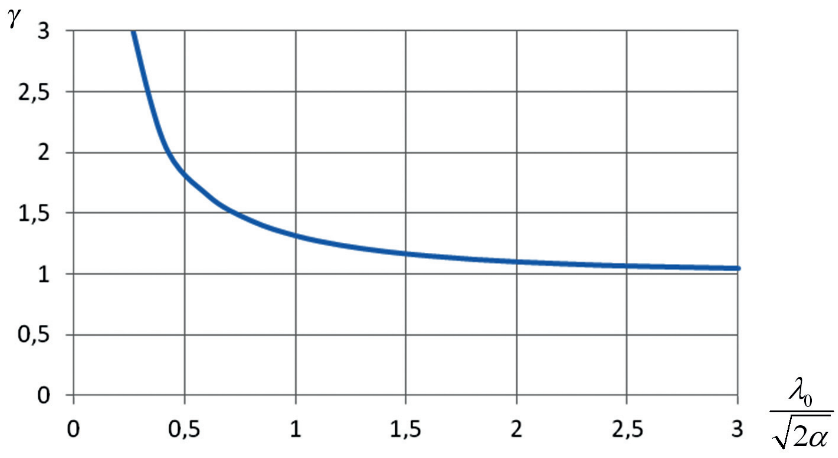


Figure 1. Dependence $\gamma = \gamma\left(\frac{\lambda}{\sqrt{2\alpha}}\right)$

$$\lambda_c = \frac{\sqrt{\frac{2\alpha}{\pi}} \cdot e^{-\frac{\lambda_0^2}{2\alpha}}}{1 - \Phi\left(\frac{\lambda_0}{\sqrt{2\alpha}}\right)}. \tag{8}$$

As we can see in (8), the numeric value $\lambda_c$ is associated with $\lambda_0$ and α by means of a quite complex dependence that is difficult to interpret in physical terms. In order to "feel" the characteristic features of this dependence let us find the coefficient:

$$\gamma = \frac{\overline{t_0}}{\overline{t}(\lambda_0, \alpha)}, \tag{9}$$

where $\overline{t}(\lambda_0,\alpha)$ is calculated in accordance with (7), $\overline{t_0} = 1/\lambda_0$ is the average life of the object that "ages" according to the law (6), but under the condition α=0 (i.e. essentially a stationary object with the failure rate $\lambda_0$). Now the physical meaning of γ becomes clear, i.e. this coefficient shows how many times the mean time to failure decreases in the ageing object compared to the time to failure of a stationary object with an identical initial failure rate. By

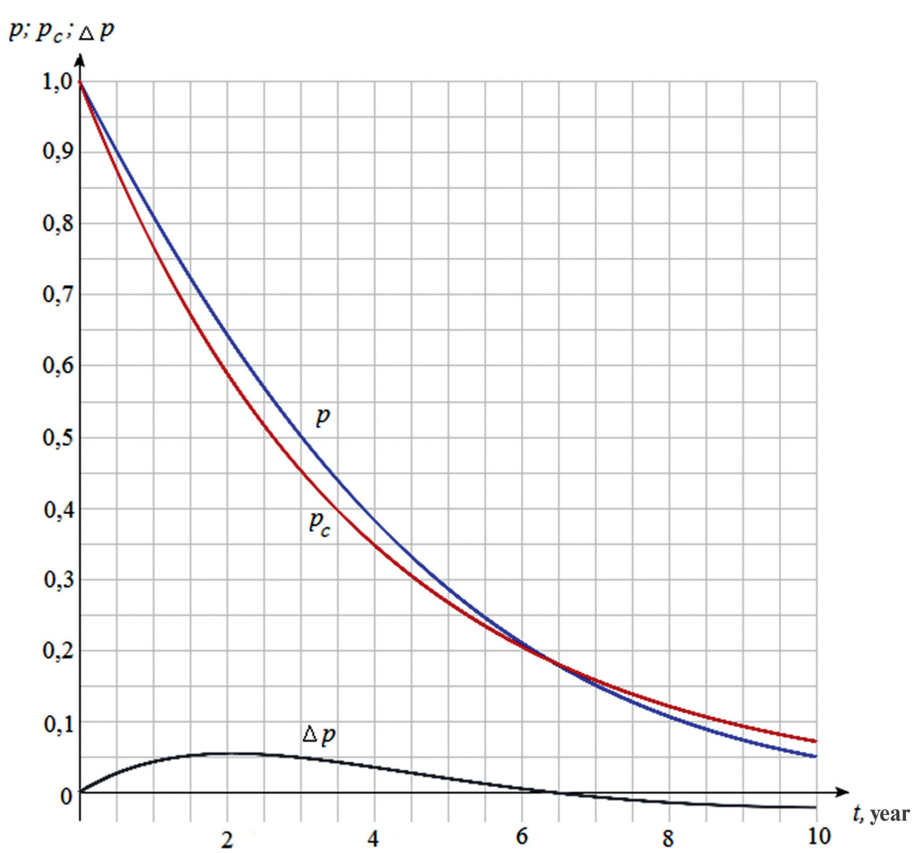


Figure 2. Dependability function of real and fake objects and difference between them

substituting this expression into (9) after some simple transformation we obtain:

$$\gamma = \frac{1}{\sqrt{\pi}} \cdot \frac{e^{-\frac{\lambda_0^2}{2\alpha}}}{\frac{\lambda_0}{\sqrt{2\alpha}} \cdot \left[1 - \Phi\left(\frac{\lambda_0}{\sqrt{2\alpha}}\right)\right]}. \quad (10)$$

As we can see, γ is the function of only the dimensionless variable $\frac{\lambda_0}{\sqrt{2\alpha}}$, which makes it possible to represent this dependence with one graph (Fig. 1).

The graph shows that as the value of the argument grows the curve tends to one, which is totally explainable: the higher is the value of failure rate $\lambda_0$, the lower is the influence (other things equal) of the object's ageing factor on its mean time to failure.

Figure 2 gives a certain idea of the concept of stationarization. It is designed for the case of a linearly ageing object with the values of parameters $\lambda_0 = 0.2$ [1/year] and $\alpha = 0.02$ [1/year$^2$].

Fig. 2 shows the graphs of the dependability functions of a real (ageing) object $p(t)$ constructed using expression (1) subject to (6):

$$p(t) = \exp\left[-\int_0^t (\lambda \ \ + \alpha t)dt\right] = \exp\left[-\left(\lambda_0 t + \frac{\alpha}{2}t^2\right)\right], \quad (11)$$

and fake stationary $p_c(t)$:

$$p_c(t) = \exp(-\lambda_c t), \quad (12)$$

where $\lambda_c$ is calculated using (8).

The graphs given in Fig. 2 – in terms of physics – can be commented in the following way. If an object's mean time to failure is interpreted as a certain technical resource, then Fig. 2 shows that during the stationarization there is a kind of a formal redistribution of the probabilities of "spending" of its parts in the course of the object's operation. The dependence graph $\Delta p(t)=p(t)-p_c(t)$ in the same figure gives an idea of how this redistribution occurs.

Even given its logical justifiability this approach cannot be used universally. The fact is that the linearly ageing object under consideration is a rare example, for which the mean time to failure can be expressed with the parameters of the characteristic of its ageing in the analytical form. Therefore it suggested to further use another approach to the definition of $\lambda_c$ that is not associated with such difficulties.

***Approach 2.*** The value of failure rate $\lambda_c$ is identified based on the formula:

$$p(t_{gv}) = p_c(t_{gv}), \quad (13)$$

i.e. out of the condition of equality of the probabilities of no-failure of the real ("ageing") and fake (stationary) object at the given moment in time $t_{gv}$.

Normally, an object's dependability is evaluated not generally, but for a certain interval $T_{frc}$, i.e. the time of forecast with regard to the current moment. Then, in view of (1) and (10) the correlation (13) becomes as follows:

$$\int_0^{T_{frc}} \lambda(t)dt = \lambda_c T_{frc}, \quad (14)$$

out of which we deduce the following:

$$\lambda_c = \frac{1}{T_{frc}} \int_0^{T_{frc}} \lambda(t)dt, \quad (15)$$

i.e. the failure rate of the fake object is defined as the mean value $\lambda(t)$ over the time of forecast.

By way of example let us find out how the formula for $\lambda_c$ will look under the two laws of object ageing: 1) in the form of an $n$-power parabola and 2) in the form of a rising exponential curve.

*Case 1.* The failure rate of a non-stationary object is as follows:

$$\lambda(t) = \lambda_0 + \alpha t^n. \quad (16)$$

By substituting this dependence into (15) we have:

$$\lambda_c = \lambda_0 + \frac{\alpha T_{frc}}{n+1} \quad (17)$$

In particular, if $n = 1$ (object considered in approach 1) expression (17) becomes as follows;

$$\lambda_c = \lambda_0 + \frac{\alpha}{2} T_{frc}. \quad (18)$$

*Case 2.*The object "ages" according to law:

$$\lambda(t) = \lambda_0 e^{\alpha t}. \quad (19)$$

Then out of (15) follows:

$$\lambda_c = \frac{\lambda_0}{\alpha T_{frc}}\left(e^{\alpha T_{frc}} - 1\right). \quad (20)$$

Expressions (17), (18) and (20) show that under this approach $\lambda_c$ depends not only on the parameters of the object's ageing characteristic, but also on the time of forecast $T_{frc}$.

The evaluation of the mean time to failure of a fake stationary object $\bar{t}_c$, as it follows from (5), now also becomes a function of $T_{frc}$ and is:

for case 1:

$$\bar{t}_c = \frac{n+1}{(n+1)\lambda_0 + \alpha T_{frc}}; \quad (21)$$

for case 2:

$$\bar{t}_c = \frac{\alpha T_{frc}}{\lambda_0\left(e^{\alpha T_{frc}} - 1\right)}. \quad (22)$$

Let us evaluate the allowable error of identification of the mean time to failure $\bar{t}$ of the real object for the case of linearly ageing object, for which $\bar{t}$ is defined by formula (7) [12]. We will evaluate the degree of proximity of $\bar{t}_c$ to the real value of $\bar{t}$ with the relative reduced error $\delta T$ that is calculated according to formula:

$$\delta\bar{t} = \left(\frac{\bar{t} - \bar{t}_c}{\bar{t}}\right) \cdot 100\% = \left(1 - \frac{\bar{t}_c}{\bar{t}}\right) \cdot 100\%, \qquad (23)$$

where $\bar{t}_c$ is calculated according to (21) (given that $n$= 1).

Under the conditions of the above numerical illustration ($\lambda_0$= 0.2 [1/year];$\alpha$= 0.02 [1/year$^2$]) as per (7) we deduce $\bar{t}$ = 3.79 years. The estimate for $\bar{t}_c$ under these parameters (as per (21) $\bar{t}_c = \frac{2}{0.4 + 0.02 \cdot T_{frc}}$. By substituting these values into (23) we have:

$$\delta\bar{t} = \left[1 - \frac{2}{3.79(0.4 + 0.02T_{frc})}\right] \cdot 100\%. \qquad (24)$$

As we can see, the relative reduced error depends on the time of forecast $T_{frc}$. The values of this error are given in the Table 1.

**Table 1**

| $T_{frc}$, годы | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $\delta\bar{t}$, % | -25,64 | -19,93 | -14,72 | -9,94 | -5,54 | -1,48 | 2,28 | 5,76 | 9,02 |

The data in the Table show that as the time of forecast grows the relative reduced error in the identification of the mean time to failure reverses sign and can reach fairly high values.

Now let us consider the dependability function and mean time to failure of an object with a periodic piecewise constant failure rate.

Let $T$ be the period of changes in the failure rate that consists of $l$ generally different time intervals (see Fig. 3, where $l$ = 3), $\tau_i$ be the time period between the beginning of the $n$-th period and the end of the $i$-th interval of this period.

For convenience, it is assumed that $\tau_0 = 0$, $\tau_l = T$, $i$= 0, 1, …, $l$. In this case $\lambda_i$ is the failure rate, $\tau_i - \tau_{i-1}$ is the duration of the $i$-th interval in the $n$-th period. In the authors' paper [13] under this change model of failure rate expressions for the dependability function $p(t)$ and mean time $\bar{t}$ to failure were obtained:

$$p(t) = e^{-\left[(n-1)A + B_{i-1} + \lambda_{i-1}\{t - [(n-1)T + \tau_{i-1}\}\right]} \text{ if}$$

$$(n-1)T + \tau_{i-1} < t \le (n-1)T + \tau_i, \qquad (25)$$

where

$$A = \sum_{j=1}^{j=l} \lambda_j (\tau_j - \tau_{j-1});$$

$$B_{i-1} = \begin{cases} 0; \ if \ i = 1 \\ \sum_{j=1}^{j=i-1} \lambda_j (\tau_j - \tau_{j-1}); \ if \ i > 1 \end{cases}$$

$$\bar{t} = \frac{1}{1 - e^{-A}} \sum_{j=1}^{j=l} \frac{1}{\lambda_j} \left[1 - e^{-\lambda_j (\tau_j - \tau_{j-1})}\right]. \qquad (26)$$

Under the practically justified assumption $\lambda T$<<1 after the Maclaurin expansion of the exponential curves under linear approximation we deduce:

$$p(t) = 1 - \left\{(n-1)A + B_{i-1} + \lambda_{i-1}[t - [(n-1)T + \tau_{i-1}]\right\} \text{ if}$$

$$(n-1)T + \tau_{i-1} < t \le (n-1)T + \tau_i; \qquad (27)$$

$$\bar{t} = \frac{1}{1 - \left[1 - \sum_{j=1}^{j=l} \lambda_j (\tau_j - \tau_{j-1})\right]} \sum_{j=1}^{j=l} \frac{1}{\lambda_j} \left\{1 - [1 - \lambda_j (\tau_j - \tau_{j-1})]\right\} = \frac{1}{\bar{\lambda}}, \qquad (28)$$

where $\bar{\lambda} = \sum_{j=1}^{l} \lambda_j \frac{\tau_j - \tau_{j-1}}{T}$ is the mean failure rate over the period $T$.

After several transformations, formulas (25) and (27) can be brought to the following form:

$$p(t) = e^{-\left\{(n-1)\bar{\lambda} T + \bar{\lambda}_{i-1} \tau_{i-1} + \lambda_i \{t - [(b-1)T + \tau_{i-1}]\}\right\}}; \qquad (29)$$

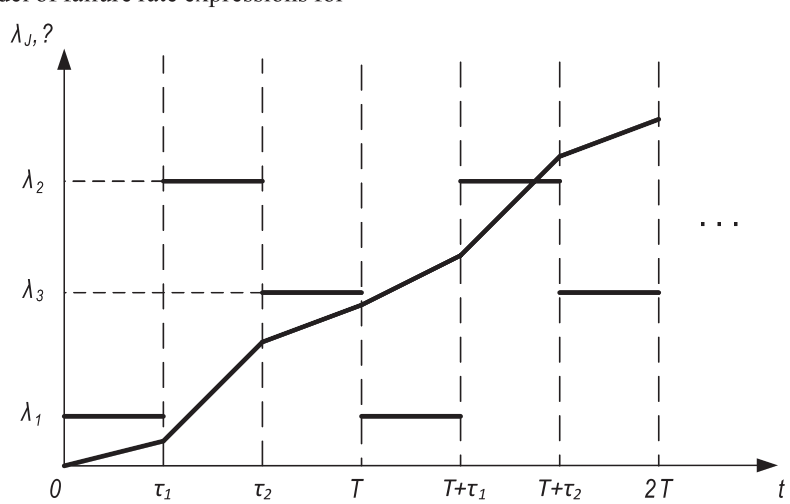


Figure 3. Failure rate model

$$p(t)=1-\{(n-1)\bar{\lambda}T+\bar{\lambda}_{i-1}\tau_{i-1}+\lambda_i[t-[(n-1)T+\tau_{i-1}]]\},\quad(30)$$

where $\bar{\lambda}_{i-1}$ is the mean failure rate over the time equal to the ($i$-1)-th interval (unlike $\bar{\lambda}$, the mean failure rate for the period $T$).

The formulas for the dependability function $(n-1)T+\tau_{i-1}< t\leq(n-1)T+\tau_i$ the summand $\bar{\lambda}_{i-1}\tau_{i-1}$ is not zero only if $i>1$.

For the purpose of calculating the probability of no failure over the fixed time $t$=$T_f$ using this formula, the value $T_f$ is reported in terms of:

$$t=T=(n-1)T+\tau_{i-1}+\Delta t,\quad(31)$$

where $0\leq\Delta t\leq\tau_i-\tau_{i-1}$

Thus, for a particular case when $T$ is divided into two intervals (in the first of which the failure rate $\lambda_1$, in the second of which $\lambda_2$) and $\frac{\lambda_2}{\lambda_1}=\alpha$, $\frac{\tau_1}{T}=\beta$, the mean time to failure is defined by the formula:

$$\bar{t}=\frac{1}{\lambda_2(\alpha\beta+1-\beta)}.$$

If this expression is obtained from (28), it is assumed that $\lambda_{\max}T<<1$, where $\max=\lambda_j$.

The results of calculation of $\bar{t}=f(\beta)$ under fixed $\lambda_2$ are given in Fig. 4. If α=1, a stationary failure flow takes place.

Let us proceed to the general case, when dependence $\lambda(t)$ is defined by a piecewise constant non-periodical function. As it was mentioned above the failure rate model is sufficiently universal.

As a non-periodical process can be considered as a periodical one with an infinitely long period, we obtain the dependability function for this case out of (29) under $n$ = 1. Indeed, the value $T$ can be chosen to be quite large and equal to the time of forecast $T_{frc}$, during which, as it was stated above, the value of the dependability function is of interest. The value $p(t$=$T_{frc})$ is so small that the use of the object under $t>T_{frc}$ is of no practical interest. Under these conditions

$$p(t)=e^{-\bar{\lambda}_{i-1}\tau_{i-1}+\lambda_i(t-\tau_{i-1})}\ \text{if}\ \tau_{i-1}<t\leq\tau_i=T_{frc}.\quad(32)$$

It remains an open question under what $\tau_{i-1}<t\leq\tau_i$ the practical usefulness of the calculations is lost. Let $p(T_{frc})$=$p_k$ be the probability of no-failure, under which the operation of a non-maintainable object end or a repairable object it is submitted to repairs. Then the duration of the predicted time period $T_{frc}$ subject to (28) is found using equation:

$$p_k=e^{-[\bar{\lambda}_{i-1}\tau_{i-1}+\lambda_i(T_{frc}-\tau_{i-1})]}.\quad(33)$$

From which

$$\ln p_k=-[\bar{\lambda}_{i-1}\tau_{i-1}+\lambda_i(T_{frc}-\tau_{i-1})]$$

and

$$T_{frc}=\frac{1}{\lambda_i}\left(-\bar{\lambda}_{i-1}\tau_{i-1}+\lambda_i\tau_{i-1}-\ln p_k\right)\quad(34)$$

Therefore, within the time interval from the beginning of object operation to $t$=$T_{frc}$ the dependability function is defined by formula (33). If it is required to calculate the probability of no-failure over the fixed time $T_f$<$T_{frc}$, the value

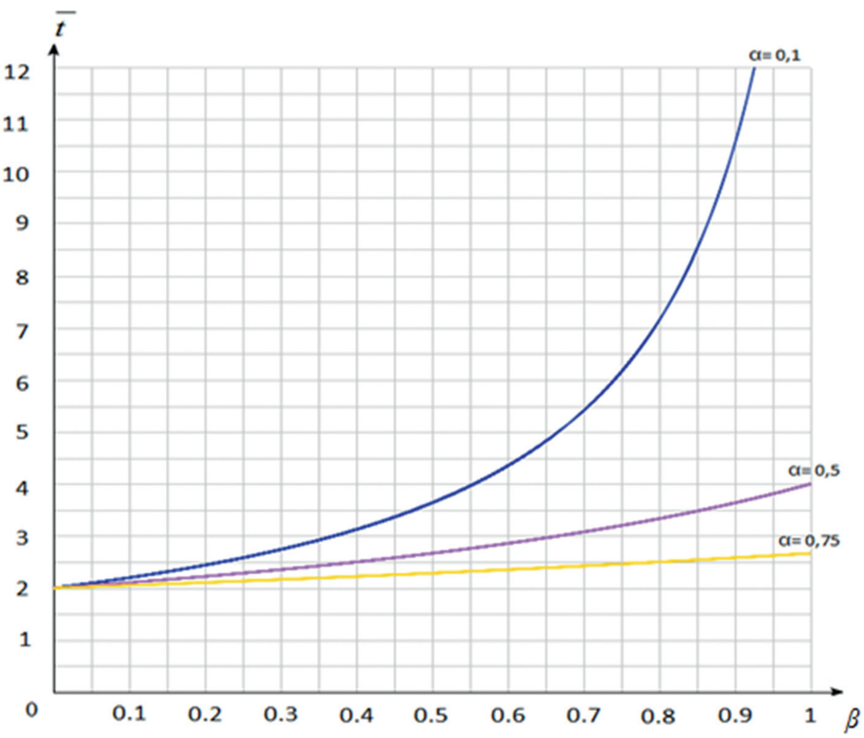


Figure 4. Dependence $\bar{t}=f(\beta)$ under different values of α

$T_f$ has the form $t=\tau_{i-1}+\Delta t$ , where $0\leq\Delta t<T_{frc}-\tau_{i-1}$ .

The linear approximation of $p(t)$ if $\lambda_{\max}T_f<<1$, where $\lambda_{\max}=\max_i \lambda_i$ is as follows:

$$p(t)=1-[\overline{\lambda}_{i-1}\tau_{i-1}+\lambda_i(t-\tau_{i-1})].$$

The mean time to failure in this case is defined by formula

$$\overline{t}=\frac{1}{\overline{\lambda}},$$

where $\overline{\lambda}$ is the mean failure rate of the time $T_{frc}$.

If linear approximation is not used, the expression of the mean time to failure $\overline{t}$ is calculated using formula (26), in which $l$ is equal to the number of intervals of constant failure rate over time $T_{frc}$.

## Conclusion

1. Solutions are shown for the tasks of identifying the mean time to failure and dependability function for various non-stationary failure flows.

2. Models of "ageing" objects are described, of which the failure rate is defined by a temporally increasing function, models of objects with periodic piecewise constant failure rate, models of objects with non-periodic piecewise constant failure rate. The solutions of tasks for various non-stationary failure flows come down to the last model after time discretization and piecewise constant approximation of the failure rate time dependence performed with the specified accuracy.

3. The shown solution results can be conveniently used in calculation of technical objects dependability.

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