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DETERMINATION OF PARAMETERS FOR THE SYSTEM OF PREVENTIVE REPLACEMENT AND REPAIR UNDER THE ACCEPTABLE FAILURE RATE

The article describes a method helping to define the scope of recovery for failure-free operation, frequency of preventive replacements and repairs of technical devices under the given failure rate level.

Keywords: *failure-free operation, scope of recovery, failure rate, repair, replacement, frequency.*

An important parameter for technical devices (TD) is safety that is understood as a TD property not to endanger life and health of people as well as environment in case of failure [1]. For example, in transport sector the necessary requirement is traffic safety ensuring. It is known that preventive replacements (PRpl) and preventive repair (PR) increase reliability, thus helping to increase TD safety. Therefore, the parameters of the system of preventive replacements and repairs (PRpl frequency, frequency and amount of PR, scope of recovery for failure-free operation) in this case shall be determined under the conditions of an acceptable (specified) TD failure-free operation level. For instance, in accordance with [2], in relation to railway signalling and remote control installations, the indicator that quantitatively characterizes an acceptable value of failure-free operation is a failure rate (FR).

As per [3], the scope of recovery for failure-free operation is suggested to be estimated by the "age" of TD α in time to failure (TTF) units. Let us consider the case when after the n of preventive repairs a TD is replaced by a new one. The change of FR is shown in Fig. 1. After minimum emergency repairs (MER) a failure rate does not change. After PR with the frequency x and the scope of recovery α, the FR goes down to value $\lambda(\alpha)$, and after PRpl with the frequency x_p – to zero. FR at the moment of PRpl and PR is $\lambda(x+\alpha)$. The values x and x_p here are measured in TTF units, and the failure rate becomes non-dimensional through multiplication by a TTF value.

Probability of failure-free operation with the frequency x_p as per Fig. 1 is determined as

$$\mathrm{P}\left(x_p\right) = P\left(x / a, n\right) = exp\left(-\int_0^{x_p} \lambda\left(x\right) dx\right) = \left(P\left(x+\alpha\right)\right)^{n+1}\left(P\left(\alpha\right)\right)^{-n}, \qquad (1)$$

where n is the number of repairs between replacements.

Special cases of expression (1):

with $n = 0$, in case of PRpl only and $\alpha = 0$, $P(x_p) = P(x)$;

with $n \to \infty$, in case of PR only, after the evaluation of an indeterminate form, we will have:

$$P(x/\alpha) = (P(x + \alpha))(P(\alpha))^{-1}. \qquad (2)$$

Considering that $x_p = \alpha + (n+1)x$ (see Fig.1), we will have:

$$x = (x_p - \alpha)(n+1)^{-1}. \quad (3)$$

Putting the value x from (3) to (1), we will have:

$$P(x_p) = [P\left(\frac{x_p + n\alpha}{n+1}\right)]^{n+1}[P(\alpha)]^{-n}. \quad (4)$$

Then FR is determined as

$$\lambda(x_p) = \lambda(x/a,n) = -\frac{[P(x_p)]'}{P(x_p)} =$$

$$= \lambda\left(\frac{x_p + n\alpha}{n+1}\right) = \lambda(x+\alpha). \quad (5)$$

Special cases of expression (5):

with $n = 0$, in case of PRpl only and $\alpha = 0$, $\lambda(x_p)=\lambda(x)$

with $n \to \infty$, in case of PR only, we will have the formula $\lambda(x/\alpha)= \lambda(x+\alpha)$,

This article considers the method for defining the parameters of the system of preventive replacements and repairs under the accepted value of TD failure rate when

$$\lambda(x/\alpha,n) \leq \lambda_g, \quad (6)$$

where λ_g is the accepted (in terms of safety ensuring) value of failure rate.

It is known that PRpl and PR are reasonably performed for TD subject to wear and ageing. For describing the failures related to wear and ageing, the normal, Weibull and gamma distributions are generally used. Besides, if the initial information is not sufficient it is reasonable to use the cosine distribution [4]. Then expression (5) with the results obtained in [4] taken into account can be represented as follows:

$$\lambda(x/a,n) = f_1\left((1-x-\alpha)v^{-1}\right)v^{-1}; \quad (7)$$

for Weibull distribution

$$\lambda(x/a,n) = bK_b^b(x+\alpha)^{b-1}; \quad (8)$$

for gamma distribution

$$\lambda(x/a,n) = \left(m^m(x+\alpha)^{m-1}\right)\times$$

$$\times((m-1)!\sum_0^{m-1}\left(m(x+\alpha)\right)^i/i!)^{-1}; \quad (9)$$

for cosine distribution

$$\lambda(x/a,n) = tg(x+\alpha), \quad (10)$$

where v is the coefficient of variation; f_1 is the tabulated function; b is the parameter of Weibull distribution shape; $K_b = G(1 + b^{-1})$. Γ is the gamma-function; m is the parameter of gamma-distribution shape.

Frequency of preventive replacements and repairs scope of recovery x_g under the specified acceptable value of failure rate are determined based on $\lambda(x/\alpha,n)=\lambda_g$ in the following way.

Weibull distribution.

With the target values α from formula (8) we will get:

$$x_g = (\lambda_g\left(bK_b^b\right)^{-1})^{\frac{1}{b-1}} - \alpha. \quad (11)$$

With $\alpha = 0$, in case of PRpl only, from formula (11) we will get:

$$x_{Pg} = (\lambda_g(bK_b^b)^{-1})^{\frac{1}{b-1}}. \quad (11a)$$

With the target values x from formula (8) we will get:

$$\alpha_g = (\lambda_g(bK_b^b)^{-1})^{\frac{1}{b-1}} - x. \quad (12)$$

With the target values x,α and n from formula (8) considering (5) we will get:

$$x_{Pg} = (n+1)(\lambda_g(bK_b^b)^{-1})^{\frac{1}{b-1}} - n\alpha. \quad (13)$$

Special cases of expression (13): with $n = 0$, when $\alpha = 0$ we will have formula (11a); with $n \to \infty$ after the evaluation of an indeterminate form, we will get (11).

2. Cosine distribution.

With the target values α from formula (10) we will get:

$$x_g = arctg\lambda_g - \alpha. \quad (14)$$

With $\alpha = 0$, in case of PRpl only, from formula (14) we will get:

$$x_{Pg} = arctg\lambda_g. \quad (14a)$$

With the target values x from formula (10) we will get:

$$\alpha_g = arctg\lambda_g - x. \quad (15)$$

With the target values x,α and n from formula (10) considering (5) we will get:

$$x_{Pg} = (n+1)arctg\lambda_g - n\alpha. \quad (16)$$

Special cases of expression (16): with $n = 0$ we will have formula (14a); with $n \to \infty$ we will have formula (14).

3. Gamma-distribution.

With the target values α from formula (9) we will get:

with $m = 2$ $$x_g = \lambda_g(4-2\lambda_g)^{-1} - \alpha; \quad (17)$$

with $m = 4$

$$x_g = \left(6\lambda_g + \left(216\lambda_g - 36\lambda_g^{\,2}\right)^{0,5}\right)(54-18\lambda_g)^{-1} - \alpha. \quad (18)$$

With $\alpha = 0$, in case of PRpl only, we will get:

with $m = 2$ $x_{Pg} = \lambda_g (4-2\lambda_g)^{-1}$; (17a)

with $m = 4$

$$x_{Pg} = \left(6\lambda_g + \left(216\lambda_g - 36\lambda_g^2\right)^{0,5}\right)(54-18\lambda_g)^{-1}. \quad (18a)$$

With the target values x from formula (9) we will get:

with $m = 2$ $\alpha_g = \lambda_g (4-2\lambda_g)^{-1} - x$; (19)

with $m = 4$

$$\alpha_g = \left(6\lambda_g + \left(216\lambda_g - 36\lambda_g^2\right)^{0,5}\right)(54-18\lambda_g)^{-1} - x. \quad (20)$$

With the target values x, α and n from formula (9) considering (5) we will get:

with $m = 2$ $x_{Pg} = (n+1)\lambda_g (4-2\lambda_g)^{-1} - n\alpha$; (21)

with $m = 4$

$$x_{Pg} = (n+1)\left[\begin{array}{c}\left(6\lambda_g + \left(216\lambda_g - 36\lambda_g^2\right)^{0,5}\right)\times \\ \times\left(54-18\lambda_g\right)^{-1}\end{array}\right] - n\alpha. \quad (22)$$

Special cases of expressions (21) and (22):

with $n = 0$ we will have respectively formulas (17a) and (18a);

with $n \to \infty$ we will have respectively formulas (17) and (18).

As it is seen from the above expressions, the frequency of preventive replacements and repairs linearly depends on the scope of recovery for failure-free operation and, respectively, the scope of recovery linearly depends on the frequency of preventive replacements and repairs.

As an example, Table 1 represents the values x_g (dividend) and x_{Pg} (divisor), calculated under the separate values λ_g, n and α, using formulas (11) and (13) in case of Weibull distribution with $b = 2$ and $b = 3$, using formulas (14) and (16) in case of cosine distribution, using formulas (17) and (22) in case of gamma-distribution with $m = 2$, and using formulas (18) and (22) in case of gamma-distribution with $m = 4$. The table shows the following. Firstly, with the shape parameter b and m increasing (decrease of a variation coefficient) the PRpl and PR frequency increases. That means that when a failure rate increases slower, preventive replacements and repairs could be performed more rarely. Secondly, with a decreasing accepted value of TD failure rate, the PRpl and PR frequency decreases. Thirdly, with a reducing scope of recovery for failure-free operation, the PR frequency decreases. Consequently, in order to ensure safety, the preventive repair of devices is reasonable to be performed with a larger scope of recovery, as in such case the PR frequency decreases, especially under low values λ_g.

As an example, let us use formula (12) to find the formula for defining the values α_g in case of Weibull distribution with the shape parameter $b = 2$

$$\alpha_g = 0,56\lambda_g - x.$$

As it is seen from the formula, firstly, with a decreasing accepted FR value and PR frequency, the acceptable value of scope of recovery for TD failure-free operation also decreases. Secondly, there is a limit value of frequency, when the value

Table 1

Distribution		Weibull $b = 2$			Weibull $b = 3$			Cosine			Gamma $m = 2$			Gamma $m = 4$		
λ_g	n	x_g/x_{Pg} with α			x_g/x_{Pg} with α			x_g/x_{Pg} with α			x_g/x_{Pg} with α			x_g/x_{Pg} with α		
		0	0,1	0,2	0	0,1	0,2	0	0,1	0,2	0	0,1	0,2	0	0,1	0,2
1	0	–/0,6	-	-	–/0,7	-	-	–/0,8	-	-	–/0,5	-	-	–/0,6	-	-
	1	-	0,54/1,17	0,44/1,07	-	0,58/1,27	0,49/1,17	-	0,68/1,47	0,58/1,37	-	0,4/0,9	0,3/0,8	-	0,44/0,98	0,34/0,88
	3	-	0,54/2,25	0,44/1,95	-	0,58/2,44	0,49/2,14	-	0,68/2,84	0,58/2,54	-	0,5/1,7	0,3/1,4	-	0,44/1,85	0,34/1,55
	5	-	0,54/3,35	0,44/2,82	-	0,58/3,61	0,49/3,11	-	0,68/4,21	0,58/3,71	-	0,4/2,5	0,3/2,0	-	0,44/2,73	0,34/2,23
0,5	0	–/0,3	-	-	–/0,5	-	-	–/0,6	-	-	–/0,2	-	-	–/0,3	-	-
	1	-	0,22/0,54	0,12/0,44	-	0,38/0,87	0,29/0,77	-	0,36/0,82	0,26/0,72	-	0,07/0,23	-	-	0,18/0,47	0,09/0,37
	3	-	0,22/0,53	0,12/0,67	-	0,38/0,87	0,29/0,77	-	0,36/0,82	0,26/1,25	-	0,07/0,37	-	-	0,19/0,85	0,09/0,58
	5	-	0,22/1,41	0,12/0,91	-	0,38/2,41	0,29/1,91	-	0,36/2,28	0,26/1,78	-	0,07/0,50	-	-	0,19/1,23	0,09/0,73

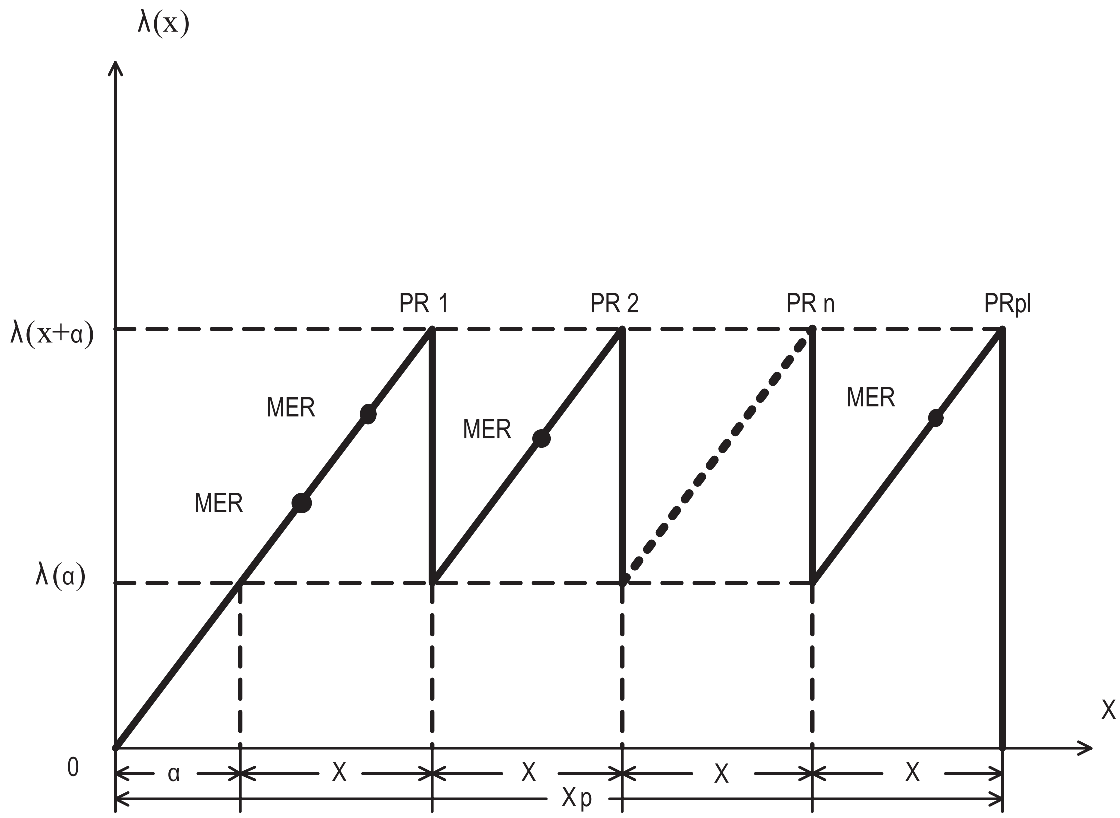

Fig. 1. Change of failure rate due to preventive maintenance and replacements

α_g becomes equal to zero, and it is necessary to perform the replacement instead of the repair of technical devices.

Conclusion

Provided that the acceptable value of TD failure rate is ensured, the proposed method makes it possible:

- with the target value of scope of recovery to determinate the frequency of repairs;

– with the target value of repair frequency to determinate the scope of recovery;

- with the target values of scope of recovery, number and frequency of repairs to determinate the time of replacement of technical devices.

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