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Method for Changepoint Detection With Sample Size Accumulation During Radio Equipment Operation

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***Abstract* – The operation system determines the efficiency of the intended use of radio equipment. The operation system includes radio equipment, documentation, operational resources, personnel, processes, data processing algorithms, etc. The operation process is associated with conditions of priori uncertainty of models, parameters, external factors, etc. The main element for monitoring is technical condition of radio equipment. In a general case, this condition can deteriorate. The problems of technical condition deterioration analysis can be considered in terms of changepoint study. The present paper concentrates on the problem of synthesis and analysis of method for changepoint detection during radio equipment operation. The detection algorithm is constructed based on Neyman–Pearson criterion with sample size accumulation. During algorithm synthesis the thresholds were calculated according to Bellman's approach. The problem of synthesis and analysis was solved by two methods: analytically and using statistical modelling. The efficiency measures for this algorithm are the probability of correct detection and mean time of decision making. The proposed algorithm has advantages in mean time of decision making compared with CUSUM detection method.**

***Keywords* – Changepoint; Data processing; Detection; Deterioration; Operation system; Radio equipment.**

I. Introduction

Air navigation service (ANS) system is one of the systems in civil aviation. This system is used for air traffic management, radio engineering support of flights, provision of aeronautical and meteorological information, etc. The ANS system operates in accordance with the standards and recommendations of ICAO and Eurocontrol requirements.

The ANS system contains two components: air traffic controllers and radio equipment [1]. There are three types of radio equipment – for communication, navigation and surveillance.

To provide reliability and maintainability of radio equipment, the operation system (OS) is used. The main element of OS is radio equipment. There are processes in OS for efficiency provision of equipment intended use, such as maintenance, repair, service life continuation, diagnostics, parameters monitoring, etc. Other important elements of OS are documentation, operational resources, personnel, etc.

Analysis showed that OS could be considered a control system. The control is ensured based on formation and implementation of corrective and preventive actions. These actions are formed according to the results of statistical data processing [2].

There are two types of data for processing: diagnostic variables and reliability parameters [3]. In case of condition-based maintenance it is necessary to prevent the equipment failure, and that is why there is a need to handle diagnostic variables [4], [5]. In case of reliability-centred maintenance, failures can occur, so in this situation reliability parameters are processed. Nowadays intelligence maintenance is developed with utilisation of processing methods based on fuzzy logic, Bayesian, semantic and neural networks, etc. [6].

Operation is the longest period of equipment life-cycle [7]. During this period, the technical condition of radio equipment can change (usually deteriorate). In this case, it is necessary to analyse the trends of change of failure rate or mean time between failures. Technical condition deterioration is associated with an increase in failure rate.

II. Literature Review and Problem Statement

In general case, the operation system of radio equipment is an object of design and improvement [8]. Literature [9], [10] review gives the opportunity to conclude that sufficient attention is paid to the maintenance process in an operation system.

Scientific organisations developed different maintenance strategies in forms of standards and guides [11]–[13]. For example, in the USA maintenance programmes MSG-1, MSG-2, MSG-3 are used for the aircraft [14] and military standards for condition-based maintenance of different equipment [15], [16].

In the OS of radio equipment, there are two main problems: optimisation of maintenance costs [17], and analysis of systems with deteriorating condition [18]. In this paper, the second problem will be considered.

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To solve the problems associated with deterioration of the technical condition, the methods of mathematical statistics and probability theory can be used [19], e.g., hypothesis testing methods, parameter estimation methods, heteroscedasticity analysis, interpolation methods, etc.

The problems of technical condition deterioration analysis can be considered in terms of changepoint study. To detect changepoint different methods, e.g., cumulative sum (CUSUM) method can be used. These methods are described in [20]. The example of synthesis and analysis of algorithms for changepoint detection was presented in [21]. In this research, the authors considered the trend of changing the mean time between failures of radio equipment. The algorithm synthesis was carried out according to Neyman–Pearson criterion with a fixed sample size.

After deterioration detection, it is necessary to estimate the reliability parameters. The example of reliability parameters estimator for a quadratic model of failure rate trend was presented in [22].

Another option of technical condition deterioration analysis is the use of sequential detectors and estimators. Such detectors and estimators have sample size that is unknown in advance [23] and have the advantage in average duration of algorithm implementation.

Thus, in the present paper the authors consider the urgent scientific problem of synthesis of changepoint detection algorithm based on Neyman–Pearson criterion with sample size accumulation and threshold calculation according to Bellman's approach.

III. Method of Changepoint Detection

The reliability of radio equipment can be described by means of the following parameters: mean time between failures, failure rate, mean time between repairs, steady state availability factor, availability function, etc. In this research, the changepoint is detected in case of failure rate change.

During normal operation of radio equipment, a failure rate usually remains constant. During the wear-out stage, a failure rate can change according to the step-function model, linear model, etc. The step-function model is the simplest one. The failure rate change in case of this model can be presented as follows:

$$\lambda(t)=\begin{cases}\lambda_1, \text{for } i\in[1;k-1],\\ \lambda_2, \text{for } i\in[k;n],\end{cases}$$

where λ_1 is a failure rate value before changepoint; λ_2 is a failure rate value after changepoint; k is a number of failure that corresponds to changepoint occurrence; n is a number of observed failures (sample size).

In a general case, values λ_1 and n are known, but k and λ_2 are unknown and random.

The formation of decisive statistics is made based on Neyman–Pearson criterion. Sample size for decision making constantly increases. The hypothesis H_0 is simple and corresponds to changepoint absence during observation time. The alternative H_1 corresponds to changepoint presence. The hypothesis H_0 is described by probability density function (PDF) $f_1(t)$, the alternative H_1 is described by PDF $f_2(t)$.

The PDFs for hypothesis and alternative are:

$$f_1(t_i)=\lambda_1^{(0)}e^{-\lambda_1^{(0)}t_i},$$

$$f_2(t_i)=\lambda_2^{(0)}e^{-\lambda_2^{(0)}t_i},$$

where t_i are times between failures of radio equipment; $\lambda_1^{(0)}=\lambda_1$ is the known failure rate, $\lambda_2^{(0)}$ is a failure rate value we need to detect.

Figure 1 presents the principle of sample size accumulation for decision making.

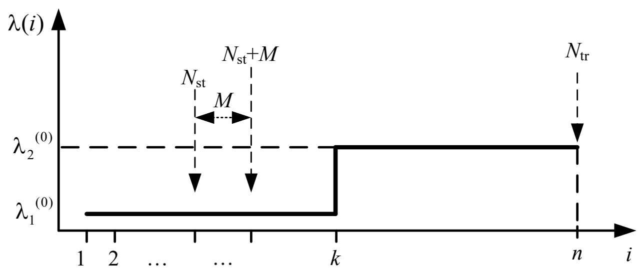

Fig. 1. The principle of sample size accumulation.

For the proposed algorithm the sample size is sequentially accumulated. The data processing starts at the point N_{st} . If changepoint is not detected, the sample size increases at M failures. The procedure continues until the decision about changepoint presence is made. The procedure is truncated at the point $n=N_{\text{tr}}=N_{\text{st}}+Ml$, where $l+1$ is a total number of data processing procedures. Therefore, the duration of algorithm implementation is a random variable.

According to Neyman–Pearson criterion we can write the likelihood functions for hypothesis H_0 and alternative H_1

$$\Phi(\vec{t}_n/H_1)=\prod_{i=1}^{n}f_2(t_i/H_1),$$

$$\Phi(\vec{t}_n/H_0)=\prod_{i=1}^{n}f_1(t_i/H_0),$$

where t_i are independent random variables (times between failures).

The likelihood ratio:

$$\Lambda(\vec{t}_n,\lambda_1^{(0)},\lambda_2^{(0)})=\frac{\Phi(\vec{t}_n/H_1)}{\Phi(\vec{t}_n/H_0)}. \quad (1)$$

In this case, (1) can be written as follows:

$$\Lambda(\vec{t}_n,\lambda_1^{(0)},\lambda_2^{(0)})=\frac{\prod_{i=1}^{n}f_2(t_i/H_1)}{\prod_{i=1}^{n}f_1(t_i/H_0)}=$$

$$= \frac{\prod_{i=1}^{N_{\text{st}}+Ml} \lambda_2^{(0)} e^{-\lambda_2^{(0)} t_i}}{\prod_{i=1}^{N_{\text{st}}+Ml} \lambda_1^{(0)} e^{-\lambda_1^{(0)} t_i}} = \left(\frac{\lambda_2^{(0)}}{\lambda_1^{(0)}}\right)^{N_{\text{st}}+Ml} e^{-(\lambda_2^{(0)}-\lambda_1^{(0)}) \sum_{i=1}^{N_{\text{st}}+Ml} t_i}.$$

To simplify the calculations, it is better to analyse the logarithm of the likelihood ratio:

$$\ln \Lambda(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)}) = \ln\left(\left(\frac{\lambda_2^{(0)}}{\lambda_1^{(0)}}\right)^{N_{\text{st}}+Ml} e^{-(\lambda_2^{(0)}-\lambda_1^{(0)}) \sum_{i=1}^{N_{\text{st}}+Ml} t_i}\right) =$$

$$= \ln\left(\frac{\lambda_2^{(0)}}{\lambda_1^{(0)}}\right)^{N_{\text{st}}+Ml} + \ln e^{-(\lambda_2^{(0)}-\lambda_1^{(0)}) \sum_{i=1}^{N_{\text{st}}+Ml} t_i} =$$

$$= (N_{\text{st}} + Ml) \ln \frac{\lambda_2^{(0)}}{\lambda_1^{(0)}} - \left(\lambda_2^{(0)} - \lambda_1^{(0)}\right) \sum_{i=1}^{N_{\text{st}}+Ml} t_i .$$

In this case, decisive statistic $\theta(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)})$ can be presented as follows:

$$\theta(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)}) = (N_{\text{st}} + Ml) \ln \frac{\lambda_2^{(0)}}{\lambda_1^{(0)}} - \left(\lambda_2^{(0)} - \lambda_1^{(0)}\right) \sum_{i=1}^{N_{\text{st}}+Ml} t_i . \tag{2}$$

In a general case, decisive statistics depends on failure rate values before and after changepoint, sample size and time of changepoint beginning.

In this algorithm, the decision about changepoint presence is made in accordance with the comparison of the decisive statistic value $\theta(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)})$ with the given value of threshold V. The alternative H_1 is true, if $\theta(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)}) \geq V$; otherwise the sample size is accumulated. The hypothesis H_0 is accepted, if $\theta(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)}) < V$ at the truncation point. Preliminary analysis showed that the threshold V is not constant. The value of threshold is calculated based on the assumption to provide the given level of probability of the first kind error α_0.

The block diagram of algorithm is shown in Fig. 2.

Let us consider the approach of threshold V calculation according to Bellman's dynamic programming [24].

First of all, it is necessary to find the PDF of decisive statistic $\theta(\vec{t}_n, \lambda_1^{(0)}, \lambda_2^{(0)})$. We assume that t_i are exponentially distributed independent random variables with the previously known failure rate $\lambda_1^{(0)}$. The characteristic function of exponential distribution is as follows:

$$\varphi(u) = \frac{\lambda_1^{(0)}}{\lambda_1^{(0)} + u}.$$

Using properties of characteristic functions, we can obtain the characteristic function of random variable sum:

$$\varphi_\Sigma(u) = \left(\frac{\lambda_1^{(0)}}{\lambda_1^{(0)} + u}\right)^{N_{\text{st}}+Ml}.$$

Such a function corresponds to PDF of the following type:

$$f(\theta / H_0) = \frac{\lambda_1^{(0)} \left(\lambda_1^{(0)} \theta\right)^{N_{\text{st}}+Ml-1}}{(N_{\text{st}} + Ml - 1)!} e^{-\lambda_1^{(0)} \theta}.$$

The obtained PDF is PDF of decisive statistics.

The family of PDFs of decisive statistics is presented in Fig. 3. The dependencies were obtained for $\lambda_1^{(0)} = 2 \cdot 10^{-6}$ and different values of sample size.

To simplify the calculation, the decisive statistic (2) can be approximated by normal PDF with mathematical expectation $m_1(\theta)$ and variance $\mu_2(\theta)$. Figure 3 shows that PDF of decisive statistic tends to the normal PDF with an increase in the sample size. This assumption can be proven by statistical simulation.

The results of simulation are shown in Fig. 4. There is a histogram for decisive statistic and corresponding normal PDF.

The histograms were built for different sample sizes: $n = 30$ (Fig. 4a) and $n = 50$ (Fig. 4b).

To check the hypothesis about normal PDF of decisive statistics by chi-square test, twenty intervals of histogram were taken and the following chi-square value was calculated:

$$\chi^2_{\text{calc}} = 25.628 \text{ for Fig. 4a},$$

$$\chi^2_{\text{calc}} = 11.606 \text{ for Fig. 4b}.$$

These values are less than a threshold value $\chi^2_{\text{th}} = 27.6$, so the hypotheses about normal PDF of decisive statistics for both cases are accepted with a significance level equal to 0.05.

Mathematical expectations of decisive statistic for hypothesis and alternative in case of approximation by normal PDF:

$$m_1(\theta / H_0) = (N_{\text{st}} + Ml)\left(\ln \frac{\lambda_2^{(0)}}{\lambda_1^{(0)}} - \frac{\lambda_2^{(0)} - \lambda_1^{(0)}}{\lambda_1^{(0)}}\right).$$

$$m_1(\theta / H_1) = (N_{\text{st}} + Ml) \ln \frac{\lambda_2^{(0)}}{\lambda_1^{(0)}} - (\lambda_2^{(0)} - \lambda_1^{(0)})\left(\frac{k-1}{\lambda_1^{(0)}} + \frac{N_{\text{st}} + Ml - k + 1}{\lambda_2^{(0)}}\right).$$

Variances of decisive statistic:

$$\mu_2(\theta / H_0) = (N_{\text{st}} + Ml)\left(\frac{\lambda_2^{(0)} - \lambda_1^{(0)}}{\lambda_1^{(0)}}\right)^2.$$

$$\mu_2(\theta / H_1) = \left(\lambda_2^{(0)} - \lambda_1^{(0)}\right)^2 \left(\frac{k-1}{\left(\lambda_1^{(0)}\right)^2} + \frac{N_{\text{st}} + Ml - k + 1}{\left(\lambda_2^{(0)}\right)^2}\right).$$

These formulas for mathematical expectations and variances are used for threshold calculation and efficiency analysis. The desirable value probability of the first kind error is calculated according to the equation:

$$\alpha_0 = 1 - \Phi\left(\frac{V - m_1(\theta / H_0)}{\sqrt{\mu_2(\theta / H_0)}}\right), \tag{3}$$

where $\Phi(\theta)$ is a standard normal cumulative distribution function.

After solving (3), we can get the threshold value:

$$V = m_1(\theta / H_0) + \sqrt{\mu_2(\theta / H_0)}\Phi^{-1}(1 - \alpha_0), \tag{4}$$

where $\Phi^{-1}(1 - \alpha_0)$ is an inverse function.

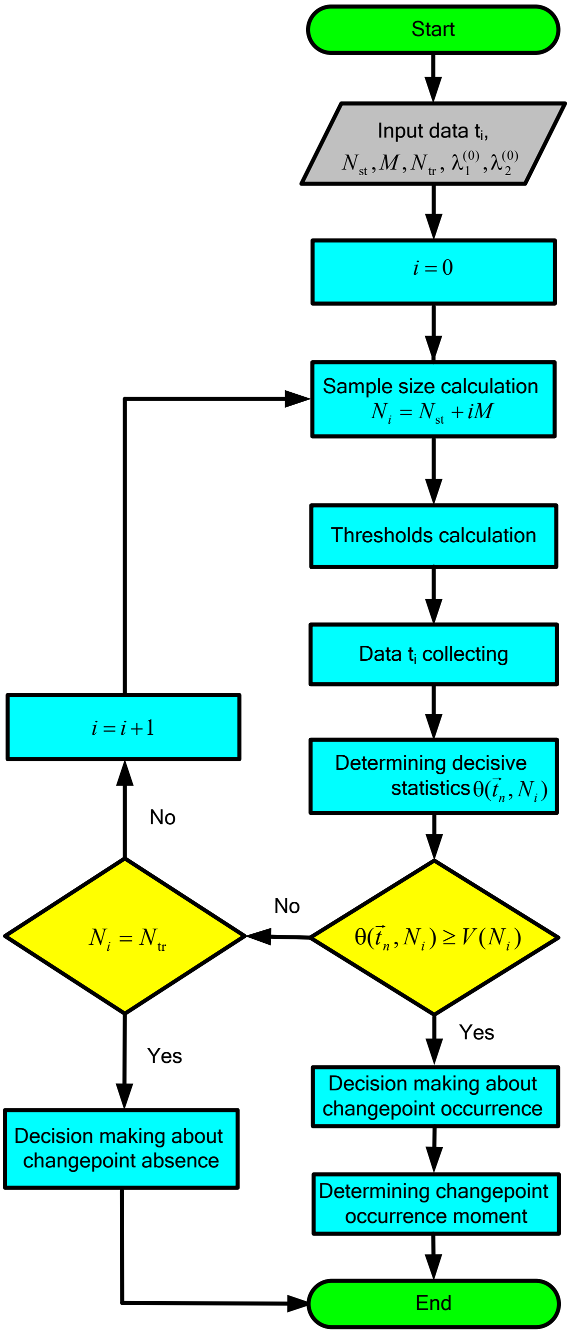

Fig. 2. The block diagram of algorithm.

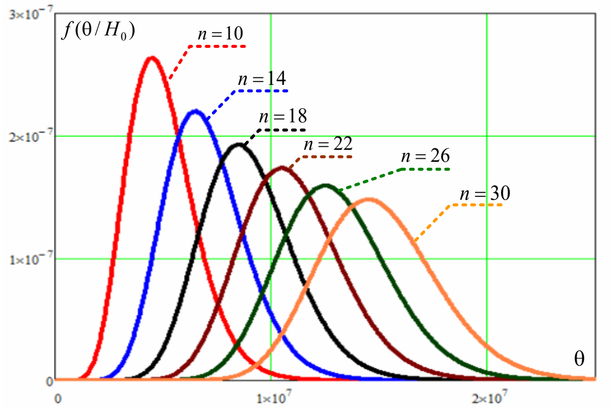

Fig. 3. PDF of decisive statistic for different sample size.

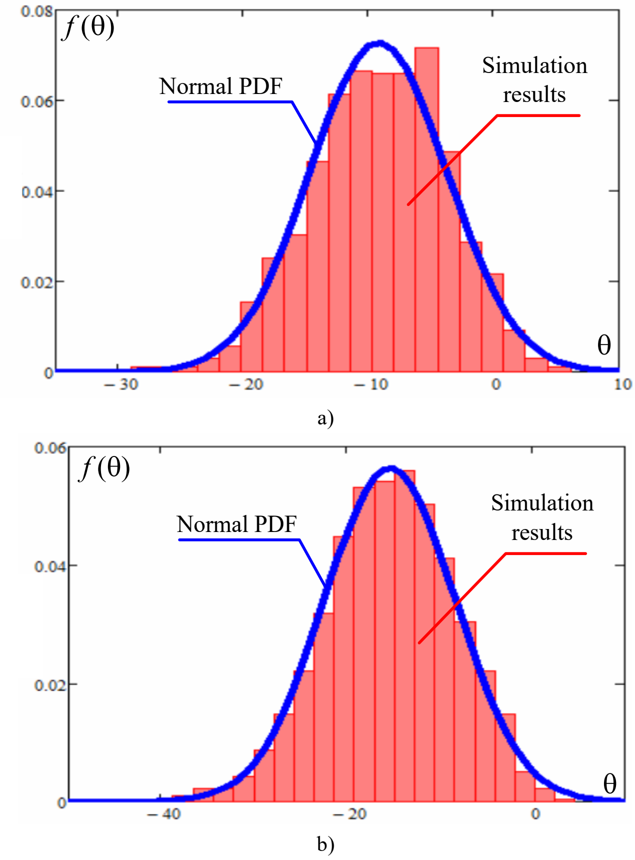

Fig. 4. The results of simulation.

According to Bellman's approach [24] the thresholds values are calculated from the last point of decisive statistic (sample number N_{tr}) to the first (sample number N_{st}). At the last point to determine the threshold, it is necessary to use equation (4). In this case, we need to provide the given level of probability α_0 of the first kind error. At the previous step, the threshold value $V(N_{tr} - M)$ depends on $V(N_{tr})$ and the probability of procedure stopping during M failure occurrence. The next thresholds are calculated similarly.

IV. Efficiency Analysis and Discussion

The probability of correct detection

$$D = \int_{V}^{\infty} N(\theta / H_1) d\theta , \qquad (5)$$

where $N(\theta / H_1)$ is normal PDF of decisive statistic for alternative H_1.

An example of calculations for the proposed method for changepoint detection is listed below. The mathematical expectations and variances for the hypothesis H_0 and the alternative H_1 are presented in Tables I and II, respectively. These tables also contain the results of statistical simulation $m_1 {}^*(\theta / H_0)$ and $\mu_2 {}^*(\theta / H_0)$. Table III presents the thresholds value for different sample size. The initial data for calculation are $N_{\text{st}} = 10$, $M = 4$, $l = 10$, $N_{\text{tr}} = 50$, $k = 25$, $\lambda_1^{(0)} = 2 \cdot 10^{-6}$, $\lambda_2^{(0)} = 4 \cdot 10^{-6}$, $\alpha_0 = 0.1$, number of procedure repetition N = 10 000.

TABLE I

Calculations Results for the Hypothesis H_0

i	$m_1(\theta/H_0)$	$m_1{}^*(\theta/H_0)$	$\mu_2(\theta/H_0)$	$\mu_2{}^*(\theta/H_0)$
10	–3.87	–2.98	10	9.71
14	–4.29	–3.91	14	13.38
18	–5.52	–5.44	18	17.50
22	–6.75	–6.63	22	21.74
26	–8.00	–7.80	26	26.10
30	–9.21	–8.99	30	29.68
34	–10.43	–10.22	34	34.96
38	–11.66	–11.47	38	40.11
42	–12.9	–12.65	42	44.01
46	–14.11	–13.85	46	47.86
50	–15.34	–15.11	50	52.89

TABLE II

Calculations Results for the Alternative H_1

i	$m_1(\theta/H_1)$	$m_1{}^*(\theta/H_1)$	$\mu_2(\theta/H_1)$	$\mu_2{}^*(\theta/H_1)$
10	–3.87	–3.08	10.0	10.86
14	–4.29	–4.33	14.0	14.70
18	–5.52	–5.58	18.0	18.30
22	–6.75	–6.80	22.0	22.21
26	–6.988	–7.12	24.5	24.68
30	–6.206	–6.37	25.5	25.61
34	–5.43	–5.55	26.5	26.40
38	–4.66	–4.71	27.5	27.27
42	–3.89	–3.99	28.5	28.65
46	–3.11	–3.24	29.5	29.57
50	–2.34	–2.50	30.5	30.58

TABLE III

Thresholds Values

i	10	14	18	22	26	30	34	38	42	46	50
V	12	12	12	12	12	12	8	4.7	0	–4	–6.3

The results of efficiency calculation for different time moments of changepoint occurrence $k = 25$ and $k = 20$ are presented in Tables IV and V, respectively. These tables also contain results of statistical simulation of the probability D^* of correct detection and mean duration $m_1(\tau)$ of decision making about changepoint occurrence.

Efficiency analysis showed that mean duration of decision making about changepoint occurrence was always less than for an identical algorithm with the fixed sample size ($n = 50$) with equal levels of probabilities of correct detection and false alarm.

TABLE IV

Efficiency Calculation Results for $K = 25$

$\lambda^* \cdot 10^{-6}$	D	D^*	$m_1(\tau)$
2.0	0.1	0.1	47.01
2.5	0.278	0.273	46.86
3.0	0.478	0.474	46.52
3.5	0.630	0.643	46.1
4.0	0.740	0.763	45.77
4.5	0.817	0.842	45.43
5.0	0.860	0.891	45.12
6.0	0.92	0.946	44.6
7.0	0.946	0.97	44.2
8.0	0.96	0.98	43.9

TABLE V

Efficiency Calculation Results for $K = 20$

$\lambda^* \cdot 10^{-6}$	D	D^*	$m_1(\tau)$
2.0	0.10	0.10	47.04
2.5	0.33	0.32	46.34
3.0	0.59	0.59	46.01
3.5	0.77	0.78	45.30
4.0	0.87	0.88	44.68
4.5	0.93	0.95	44.12
5.0	0.95	0.97	43.55
6.0	0.98	0.99	42.72
7.0	0.99	1	42.10
8.0	1	1	41.71

Figure 5 presents the dependencies of probability (5) of correct detection of radio equipment technical condition deterioration. These dependencies are built for different time moments of changepoint occurrence. The analysis also showed that the probability of correct detection increased with decreasing time moments of changepoint occurrence.

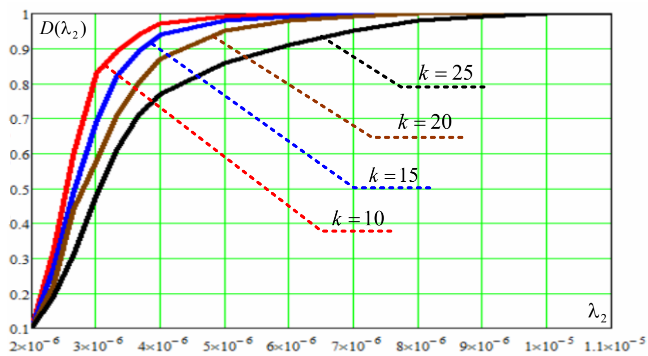

Fig. 5. The operating characteristics of changepoint detection.

V. Conclusion

The present paper concentrates on the problem of synthesis and analysis of method for changepoint detection during radio equipment operation. The detection algorithm is constructed based on Neyman–Pearson criterion with sample size accumulation.

The main property of detection algorithm is sequential dynamic decision making about changepoint occurrence. The analysis showed that for such an algorithm decision making threshold was not constant. Bellman's approach was used for threshold calculation. Estimates of the probabilities D and D^* of correct detection showed that the proposed method for determining the thresholds allows providing the probability of false alarm α_0 for hypothesis H_0.

The decisive statistics was approximated with usage of normal PDF. The simulation results proved good coincidence between D and D^*.

The analysis of estimates of mean duration of decision making about changepoint occurrence showed that an increasing failure rate leads to $m_1(\tau)$ decrease. Moreover, mean duration tends to decrease in case of time moments of a decrease in changepoint occurrence. It should be noted that the researched algorithm has advantage in terms of duration approximately 10–15 % compared with CUSUM detection method.

The results can be used during design and improvement of operation system of radio equipment.

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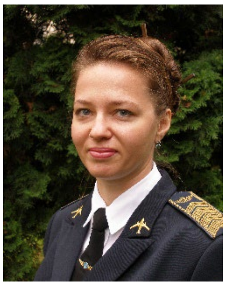

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