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Calculation of reliability of submersible electrical pumps on base of censored samples processing of service data

Habibov I.A, Abbasova S.M.

Abstract – A calculation procedure of* reliability of electrical centrifugal pumps installations (ECPI) and their separate components on service data, *based on representation of reliability by a polynomial of a certain degree* n *has been developed. Estimations of the distribution function of a prefailure life and probability of no-failure operation for ECP installations are got with use of the root method of construction of distribution density of random quantity. An example of numerical calculation was given.

***Index Terms* – censored sample, parametric and nonparametric methods, root method, statistical data processing.**

I. INTRODUCTION

Since failures of submersible electrical centrifugal pumps installations (ECPI) have randomicity, it is possible to get scientifically-motivated characteristics of reliability of submersible installations by means of statistical reliability theory which is one of the sections of mathematical statistics. However using the classical methods of mathematical statistics for processing of data about exploitation of ECPI has essential restrictions because given methods provides the calculation on samples, consisting only of refused products. One should have in view that in a process of reliability analysis it happens to face situations, when a certain part of objects does not refuse for an observation period, but the other part refuses, but exact failure moments are unknown. In such situations a necessity of carrying out the statistical reliability analysis on base of specific samples appears, the main feature of these samples is absence of information about failure moments of the controlled part of products.

II. PROBLEM DESCRIPTION

The process of appearance of failure moment uncertainty is named censoring. Censored sample is a sample [6], elements of which are prefailure lives and life lengths before censoring, or only values of life length before censoring. Such samples require the special processing methods. In this connection classical methods of mathematical statistics are not widespread in an oil producing sector. It is shown in work [1] that processing methods of censored samples must be used for calculation of reliability of ECPI and their components on service data.

On basis of given methods we have developed calculation procedure of reliability of ECPI and their separate components on service data, based on representation of $\ln P(t)$ ($P(t)$ is a probability of no-failure operation at the moment t) by a polynomial of a certain degree n.

Estimations of the distribution function of a prefailure life and probability of no-failure operation for ECP installations are got with use of the root method of construction of distribution density of random quantity offered in [2] and developed in [3] for censored samples. An example of numerical calculation was given.

III. THE ROOT METHOD OF ESTIMATION OF DISTRIBUTION DENSITY OF A PREFAILURE LIFE ON CENSORED DATA

Suppose that there is following statistical information about failures, presented in the form of full and censored life lengths:

1) $\vec{\xi} = \{\xi_1, \ldots, \xi_p\}$ - an array of full life lengths, p – an amount of failures with known life length;

2) $\vec{\Delta} = \{\Delta_1, \ldots, \Delta_S\}$ - an array of censoring intervals, where $\Delta_i = (l_i; r_i)$ - an interval, s - an amount of censoring intervals;

3) $\vec{\nu} = \{\nu_1, \ldots, \nu_S\}$ - a vector, ν_i elements of which present random number of failures, occurring in the i -th interval of censoring.

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It is obviously that $n = p + q$ is a total amount of observations, where $q = \sum_{j=1}^{S} \nu_j$ is a total amount of censored observations.

Thereby, totality of $\vec{\Delta}$ intervals and $\vec{\nu}$ frequencies represents grouped information about a failure – a most commonly case of censoring.

On the basis of indicated information we shall build the estimations of density and the distribution function of a prefailure life with use of the root method of estimation of distribution density on censored data [3].

In accordance with the method [3] an estimation of sought density $f_\xi(x)$ of the random quantity ξ (ξ is a prefailure life) is sought in the form of

$$\hat{f}_\xi(x) = [\psi(x)]^2, \qquad (1)$$

where

$$\psi(x) = \sum_{i=1}^{m} c_i \varphi_i(x), \qquad (2)$$

$\{\varphi_i(x)\}$ is an orthonormal system in $[a,b]$, $\{c_i\}$ are the real coefficients of expansion which are subjecting to estimation.

As basis functions we shall take

$$\varphi_k(x) = \sqrt{\frac{2}{b-a}} \cdot \sin\left(k\pi \cdot \frac{x-a}{b-a}\right), \quad k = 1,2,\ldots \qquad (3)$$

Using the maximum-likelihood method (MLM), we come to an iteration scheme for the coefficients $\{c_i\}$:

,

$$c_i^{(q+1)} = \alpha c_i^{(q)} + \frac{1-\alpha}{2\lambda^{(q)}} \left[2\sum_{k=1}^{p}\sum_{j=1}^{m} c_j^{(q)} \frac{\varphi(\xi_k)}{\varphi_j(\xi_k)} + \sum_{h=1}^{S} \frac{\nu_h \left(\frac{\partial \hat{F}^{(q)}(r_h)}{\partial c_i^{(q)}} - \frac{\partial \hat{F}^{(q)}(l_h)}{\partial c_i^{(q)}} \right)}{\hat{F}^{(q)}(r_h) - \hat{F}^{(q)}(l_h)} \right],$$

(4)

where $\lambda^{(q)}$, $\hat{F}_\xi^q(x)$ and $\frac{\partial \hat{F}_\xi^{(q)}}{\partial c_i^{(q)}}$ are defined accordingly on formulas (for reduction of a writing we shall omit the upper index q in them):

$$\lambda = p + \frac{1}{2}\sum_{h=1}^{S} \frac{\nu_h}{\hat{F}_\xi(r_h) - \hat{F}_\xi(l_h)} \sum_{i=1}^{m} c_i \left[\frac{\partial \hat{F}_\xi(l_h)}{\partial c_i} - \frac{\partial \hat{F}_\xi(r_h)}{\partial c_i} \right] \qquad (5)$$

$$\hat{F}_\xi(x) = \frac{x-a}{b-a} - \frac{1}{2\pi d}\sum_{i=1}^{m} \frac{c_i^2}{i}\varphi_{2i}(x) + \frac{1}{\pi d}\sum_{i=1}^{m}\sum_{j=1}^{m} c_i c_j \left(\frac{\varphi_{i-j}(x)}{i-j} - \frac{\varphi_{i+j}(x)}{i+j} \right), \qquad (6)$$

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$$\frac{\partial \hat{F}_{\xi}(x)}{\partial c_i} = \frac{2}{\pi d}\left(\sum_{j \le i}^{m} c_j\left[\psi_{i-j}(x) - \psi_{i+j}(x)\right] - c_i \psi_0(x)\right), \quad (i = 1, \ldots, m), \qquad (7)$$

where

$$d = \sqrt{\frac{2}{b-a}}, \quad \psi_k(x) = \frac{\psi_k(x)}{k}, \quad k = 1, 2, \ldots, \qquad \psi_0(x) = \pi d \frac{x-a}{b-a}. \qquad (8)$$

The parameter α $(\alpha \in (0;1))$ influences greatly upon stability and velocity of iterative procedure convergence (14). Assigning initial approximation $\vec{c}^{(0)} = (1, 0, \ldots, 0)$, we get the convergent sequence $\vec{c}^{(1)}$.

IV. ESTIMATION OF RELIABILITY OF SUBMERSIBLE ECP ON THE BASIS OF THE ROOT ESTIMATION OF DISTRIBUTION DENSITY ON CENSORED DATA

We shall consider statistics from [4], collected on 250 wells, in which 1152 submersible pumps were worked in the course of year (look at table II).

Table I. Results of primary processing of statistical information about failures of submersible ECP

Interval of life lengths, *day*	Number of failures on categories of wells					Number of failures in the interval of lifelengths
	«N»	«S»	«C»	«CS»	«CS»	
0-15				0		
15-30			22	38		60
30-45			28	87	10	125
45-60		19	30	90	30	169
60-75	15	23	26	70	36	170
75-90	20	30	12	40	44	146
90-105	35	34	-	8	28	105
105-120	45	29	6	5	15	100
120-135	60	22	-		4	86
135-150	48	18	-			66
150-165	43	12	-			55
165-180	37	5	4			46
180-195	24					24
Total	327	192	128	338	167	1152

Previously the wells were divided into categories. The wells were chosen within each category on contents of chemical and mechanical admixtures on [4]:

- "normal" (N), in which the complications in functioning of the equipment because of sand and corrosions did not appear;
- "sand" (S), in which high concentration of sand in production of the well brought about the formation of sand plugs and abrasion of the electrical pump details;
- "corrosion" (C), in which private mortality of submersible electrical pumps because of corrosion was observed;
- "corrosion-sand" (CS), in which complications appeared as a result of simultaneous influence of the pump and corrosion upon work of submersible electrical pumps.

In turn "corrosion-sand" wells are divided into two groups: wells with big contents (50 ml H^2S and 1,3 g/l sand) (CS) and small contents (CS)' of the admixtures.

For the further analysis we shall content with wells of CS category, being in the most complex operation conditions, which were processed by means of 338 submersible ECP. For censoring intervals we shall take 8 time intervals (in days): [0; 15), [15; 30), [30; 45), [45; 60), [60; 75), [75, 90), [90, 105), [105, 120].

Suppose that $a = 0,\ b = 120,$ then $d = \sqrt{\frac{2}{120}} = 0{,}016.$

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In accordance with (3) the orthonormal basis on [0;120] will take the form

$$\varphi_k(x) = 0{,}016 \cdot \sin\left(k\pi \frac{x}{120}\right), \quad k = 1,2,...$$

We get:

$$l_1 = 0,\ r_1 = 15; l_2 = 15, r_2 = 30; l_3 = 30,\ r_3 = 45;\ l_4 = 45,\ r_4 = 60;$$

$$l_5 = 60,\ r_5 = 75; l_6 = 75, r_6 = 90; l_7 = 90,\ r_7 = 105;\ l_8 = 105,\ r_8 = 120.$$

Since we do not know failure moments, then the vector $\vec{\xi}$ is absent in source information ($p = 0$); $\nu_1 = 0,\ \nu_2 = 38,\ \nu_3 = 87,\ \nu_4 = 90,\ \nu_5 = 70,\ \nu_6 = 40,\ \nu_7 = 8,\ \nu_8 = 5.\ (s = 8).$

We shall place $m = 3$ in the expansion (12) (an estimation accuracy increases with growth of m) and $\alpha = 112$ in the iterative procedure (14); $\vec{c}^{\,(0)} = (1,0,0).$

Taking into account $p = 0,$ the iterative process (4) takes the following form:

$$c_1^{(q+1)} = \alpha c_i^{(q)} + \frac{1-\alpha}{2\lambda^{(q)}} \sum_{h=1}^{S} \frac{\nu_h \left(\dfrac{\partial \hat{F}_\xi^{(q)}(r_n)}{\partial c_i^{(q)}} - \dfrac{\partial \hat{F}_\xi^{(q)}(l_h)}{\partial c_i^{(q)}} \right)}{\hat{F}_\xi^{(q)}(q_h) - \hat{F}_\xi^{(q)}(l_h)} \qquad (i = 1,...,m), \qquad (9)$$

where

$$\lambda^{(q)} = \frac{1}{2} \sum_{h=1}^{S} \frac{\nu_h}{\hat{F}_\xi^{(q)}(r_h) - \hat{F}_\xi^{(q)}(l_h)} \sum_{i=1}^{m} c_i^{(q)} \left[\frac{\partial \hat{F}_\xi(l_h)}{\partial c_i^{(q)}} - \frac{\partial \hat{F}_\xi(r_h)}{\partial c_i^{(q)}} \right] \qquad (10)$$

Superimposing on the interval (a,b) the net $\{x_j\}$ $(j = 0,1,...,n)$ $x_0 = a,\ x_j = a + j \cdot \delta$ with a certain sampling step δ, one can calculate in points $t_j = x_j$ $(j = 0,1,...,n)$ values of functions $\hat{f}_\xi(x), \hat{F}_\xi(x)$ and $\hat{\mu}(t)$ according to formulas (1), (6) and (11) under limiting values $c_i^o = \lim_{q\to\infty} c_i^{(q)}$ and build the graphs of these functions in EXCEL.

The calculation results of the root estimation of distribution density of a prefailure life $\hat{f}(t),$ of the distribution function $\hat{F}(t)$ of a prefailure life and of probability $\hat{P}(t)$ of no-failure operation, of failure rate $\hat{\mu}(t)$ were provided in table II and represented on fig. 1, 2, 3 accordingly.

"Spectral analysis" of estimation of failure rate $\hat{\mu}(t)$, calculated on following formula, presents a special interest

$$\hat{\mu}(t) = (1 - P(\Delta t)) \cdot \frac{N\Delta t}{N(\Delta t)}, \qquad (11)$$

Where $P(\Delta t)$ - probability of no-failure operation in the interval $(t, t + \Delta t)$ (it was taken Δt=1 in calculations); N - a total number of pumps $(N = 338); N(\Delta t) = N - \nu(\Delta t),$ $\nu(\Delta t)$ - a number of refused pumps in the interval $(t, t + \Delta t)$.

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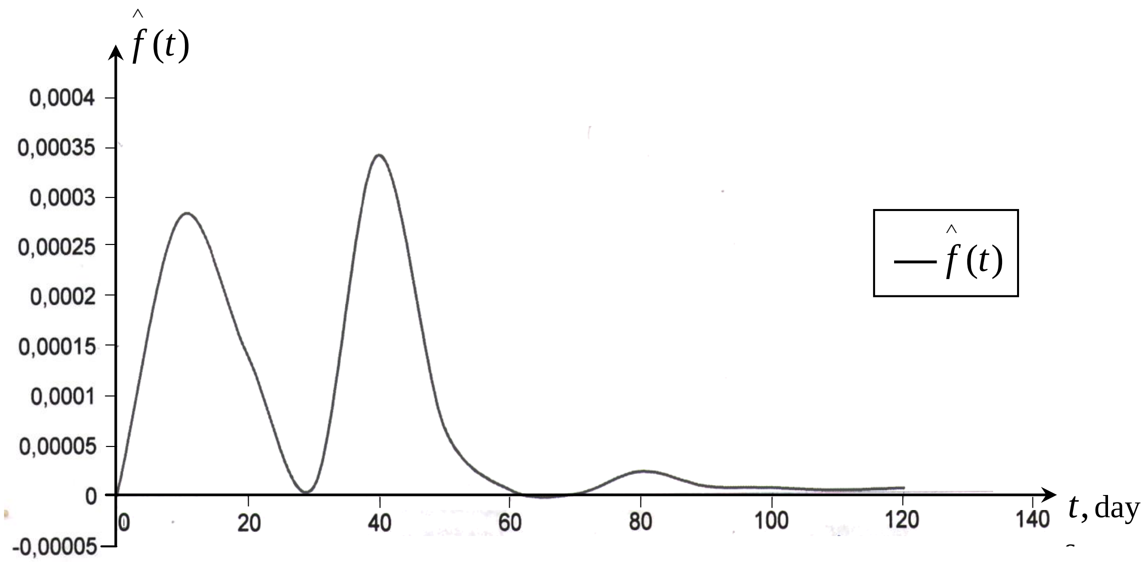

Fig. 1. The root estimation of distribution density of a prefailure life $\hat{f}(t)$.

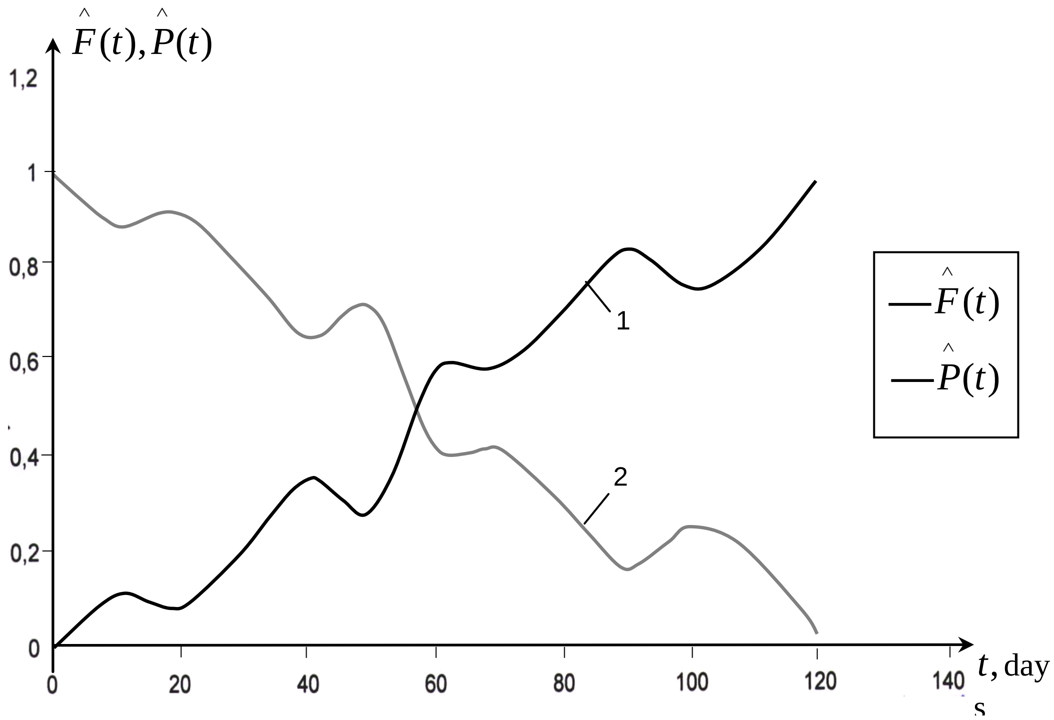

Fig. 2. Root estimations of the distribution function $\hat{F}(t)$ of a prefailure life (curve 1) and of probability $\hat{P}(t)$ of no-failure operation (curve 2).

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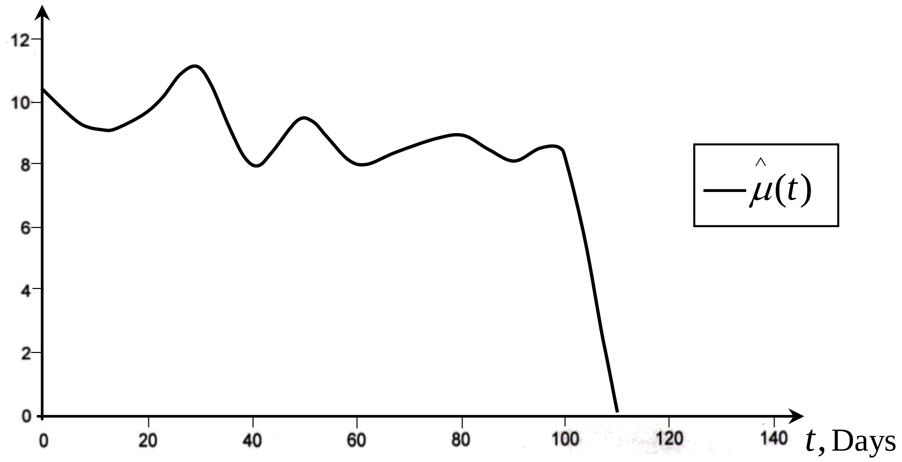

Fig. 3. A root estimation of failure rate $\hat{\mu}(t)$.

Table II:The calculation results of the root estimation

	$\hat{f}(t)$	$\hat{F}(t)$	$\hat{\mu}(t)$	$\hat{P}(t)$
0	0	0	10.41408	
10	0.00028	0.110522	9.16463	0.889478
20	0.000141	0.085077	9.685899	0.914923
30	8.21E-06	0.20392	11.09953	0.79608
40	0.000341	-0.35263	8.001927	0.64737
50	6.72E-0.5	0.286693	9.492943	0.713307
60	4.60E-06	0.57882	8.045921	0.42118
70	2.27E-07	0.587172	8.550102	0.412828
80	2.24E-05	0.703988	8.946811	0.296012
90	7.23E-06	0.831636	8.095003	0.168364
100	4.97E-06	0.751316	8.307292	0.248684
110	0.000225	0.814185	1.92E-06	0.185815
120	0.00042	0.977101		0.022899

Besides the statistical noise, each sudden change (hunch) of the function of failure rate (fig. 3) can be connected with objective reasons of failures. In the considered case the function of failure rate has two hunches. The technological analysis of failures reasons in the zone of extremums of the function $\hat{\mu}(t)$ shows that the first hunch is connected with shortcomings of fulfilment of repair work, including preventive. The Second hunch is connected with failures of separate components of pump parts, conditioned by construction imperfection of pumping units.

V. CONCLUSION

1. In real carried out research of objects for reliability presence of full prefailure life is absent, or exact instants of failure are not known, but there is only information about amount of failures in certain observation moments that is to say we deal with censored samples processing.

2. Using the parametric methods of statistical information analysis requires suppositions about type of distribution law of the observed random quantities. However, as a rule, it is impossible indicate any deep reasons, on which a concrete distribution of observation results must enter that or other parametric family. That

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is why nonparametric methods, to the class of which the root method of estimation of distribution density belongs, play more and more part at estimation of distribution density

3. The root method of estimation of distribution density is applicable to processing of data about failures, presented in the form of full life lengths (with exactly known times of prefailure lives) and/or censored life lengths, when only an amount of life lengths in determined time periods of observations is known

4. The given method allows making an additional deep technological analysis of reliability on base of the analysis of failure rate functions what is not characteristic for parametric methods.

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AUTHOR BIOGRAPHY

Habibov Ibrahim Abulfaz, Doctor of technical sciences, professor Azerbaijan State University of Oil and Industry (ASUOI). Baku, Azerbaijan (AZ1010, Baku, Azadlyg avenue, 20), tel. (050)216-48-87.

Sevinj Malikovna Abbasova, assistant Azerbaijan State University of Oil and Industry (ASUOI). Baku, Azerbaijan (AZ1010, Baku, Azadlyg avenue, 20), tel. /fax: (055) 350-84-30