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Formation of estimates of reliability indicators for active elements in gas transport systems on the basis of refusals statistics

Keywords

gas transport systems, gas-compressor units, reliability, statistics, refusals, mathematical methods

Abstract

The problem of equipment functioning reliability in gas transport systems is extremely urgent. This article deals with the algorithm of estimation and prediction of reliability factors of gas-compressor units and automatic systems, which uses statistical information about elements failures as input data. This algorithm is based on methods of mathematical statistics and regression analysis and provides the opportunity to obtain predictive estimate of failure rate, time between failures and availability function. In addition, the article describes the outcome of algorithm action, disagreement between industrial data about systems functioning and technical specification of these systems.

1. Introduction

Gas transport systems (GTS) play important role in ensuring power safety of the Russian Federation, and the European countries. On the other hand processes of transportation of gas, as well as other processes of oil and gas sector, are technologically dangerous. In these conditions the reliability criterion of functioning of GTS becomes dominating.

Reliability of functioning is defined by a complex set of technology, production, technical, ecological and organizational factors. An active element of GTS is gas-compressor units (GCU). GCU belong to installations of long-term use, the general which resource of an operating time reaches 100 thousand hours and more. However separate elements of the unit can have a limited resource, for example the engine, turbine shovels.

As GCU is Basic Element of GTS, functioning of Uniform System of Gas supply (USG) of the Russian Federation directly depends on reliability, quality, service conditions and GCU maintenance. Procedures of maintenance of GCU in technically working order include supervision, check of a technical status, and also elimination of technical malfunctions. At operation reliability augmentation is reached by the rational organization of maintenance and the repair, allowing to reduce number of crashes and losses because of their emergence, to prolong the repair period, to reduce costs for each planned repair. The system of operation of GCU influences cost of operation of object as a whole, cost of repair work, duration of idle times, costs of equipment replacement.

In the Russian Federation the tendency of development of automated systems of technological processes control defined the automated systems of supervisory control (ASSC) as the main direction, it is thus noted that management of local objects is transferred to minimally manned operations [1]. At minimally manned operations of such objects requirements to reliability functioning of system, diagnostics of a technical status of systems amplify. For supervisory control there is a problem of continuous condition monitoring of technology equipment and reliability of carried-out functions as the subject of management should have exhaustive idea of a system status as a whole.

The solution of this task, first of all, is caused by a number of features, such as a lack of statistical data on refusals; lack of comprehensive approaches and reliability assessment techniques; absence of the relevant information systems, etc.

In these conditions there is actual a development of information and analytical system (IAS) of an assessment and monitoring of reliability of ASSC (in which the assessment of indicators of reliability of active elements plays important role) [2].

The system of an assessment and monitoring of reliability is intended for increase (on the basis of the current and look-ahead information) to operational reliability of functioning of ASSC by technological processes in gas transport at the expense of timely organizational measures for reservation, replacement of the equipment and carrying out scheduled preventive works.

2. An engineering approach of receiving estimates of indicators of reliability within Weibull-Gnedenko's two-parametrical model of time distribution to the refusal

Formation of look-ahead characteristics of probability of no-failure operation in created IAS is described by Weibull-Gnedenko's model. Within a considered fragment of technological active elements - GCU and system of automated control (SAC) of GCU, on the basis of initial models is defined a number of the characteristics, allowing to estimate failure rate.

Weibull -Gnedenko's distribution takes an important place among distributions of time of no-failure operation of the systems consisting of groups of a large number of elements which refusals occur mutually independently so refusal of any of elements leads to refusal of all system (the principle of «the weakest link»). Many devices contain considerably number of identical or close elements on a design, being in approximately identical operational conditions. For example, the gas turbine (a part GCU) has a large number of shovels, GCU automatic equipment (SAC GCU) systems – considerable number of sensors, various elements of radio-electronic equipment, electronic payments etc. If elements repeating in one device are defining in relation to time of no-failure operation of the device, the scheme leading to distribution of Weibull-Gnedenko is formed.

For the first time in technical applications this distribution was offered in work of the Swedish physicist W. Weibull [3] in 1939 for the description of distribution of durability of materials, without any mathematical justification for purely heuristic reasons. Strict mathematical consideration of the specified distribution was executed by the Russian mathematician B. V. Gnedenko [4] in 1941 which gave theoretical justification of this distribution, having proved that it is one of three types of limiting distributions of selective maxima. Therefore, while abroad this distribution is called as Weibull's distribution, in Russian statistical literature it is known as Weibull-Gnedenko's distribution.

Random variable ξ submits to Weibull -Gnedenko's distribution if her function of distribution has the following appearance:

$$F(t) = \begin{cases} 1 - e^{-(\alpha t)^{\beta}}, t \ge 0 \\ 0, \qquad t < 0 \end{cases} \tag{1}$$

$$f(t) = \begin{cases} \alpha^{\beta} \beta t^{\beta - 1} \cdot e^{-(\alpha t)^{\beta}}, \quad t > 0 \\ 0, \qquad t \le 0 \end{cases} \tag{2}$$

where α is called as a scale parameter $(\alpha > 0)$, and β is called shape parameter $(\beta > 0)$, on which the type of the schedule of density of distribution (*Figure 1*) depends:

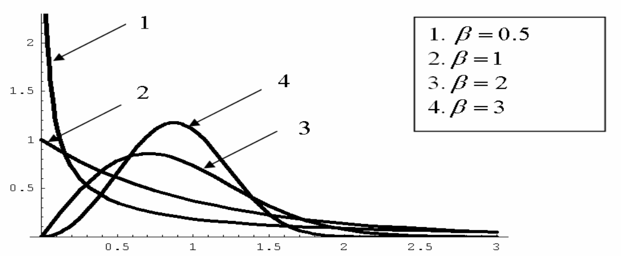

Figure 1. Forms of curve density of distribution of Weibull-Gnedenko for some values of parameters β (at α = 0.5).

The mean and the variance of random variable ξ are, respectively,

$$M\xi = \frac{1}{\alpha}\Gamma\left(1 + \frac{1}{\beta}\right),$$

$$D\xi = \frac{1}{\alpha^2}\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)\right], \tag{3}$$

where $\Gamma(x) = \int_0^{+\infty} t^{x-1} e^{-t} dt$ − Eulerian gamma-function. The most important numerical characteristics of random variable ξ include function of the special type which values can be found only with numerical methods. Therefore a problem of theoretical studying of distribution of Weibull-Gnedenko by means of asymptotic technique is actual. As a result of carried study asymptotic decompositions for main constants of random variable ξ where received with the use of mentioned technique:

$$M\xi = \frac{1}{\alpha}\left[1 - \frac{\gamma}{\beta} + \frac{1}{2}\left(\gamma^2 + \frac{\pi^2}{6}\right)\frac{1}{\beta^2} - \frac{1}{6}\left(\gamma^3 + \frac{\gamma\pi^2}{2} + 2\cdot\zeta(3)\right)\frac{1}{\beta^3} + \frac{1}{24}\left(\gamma^4 + \gamma^2\pi^2 + 8\gamma\cdot\zeta(3) + \frac{3\pi^4}{20}\right)\frac{1}{\beta^4} -\right.$$

$$\left.- \frac{1}{1440}\left(12\gamma^5 + 20\gamma^3\pi^2 + 240\gamma^2\cdot\zeta(3) + 9\gamma\pi^4 + 40\pi^2\cdot\zeta(3) + 288\cdot\zeta(5)\right)\frac{1}{\beta^5}\right] + o\left(\frac{1}{\beta^5}\right), \quad (\beta \to \infty)$$

$$D\xi = \frac{1}{\alpha^2}\left[\frac{\pi^2}{6}\frac{1}{\beta^2} - \left(\frac{\gamma\pi^2}{3} + 2\cdot\zeta(3)\right)\frac{1}{\beta^3} + \left(\frac{\gamma^2\pi^2}{3} + \frac{29}{360}\pi^4 + 4\gamma\cdot\zeta(3)\right)\frac{1}{\beta^4} -\right.$$

$$\left.- \frac{1}{180}\left(40\gamma^3\pi^2 + 29\gamma\pi^4 + 720\gamma^2\cdot\zeta(3) + 140\pi^2\cdot\zeta(3) + 1080\cdot\zeta(5)\right)\frac{1}{\beta^5}\right] + o\left(\frac{1}{\beta^5}\right), \quad (\beta \to \infty)$$

$$Var\xi = \frac{\sqrt{D\xi}}{M\xi} = \frac{1}{\sqrt{6}}\left[\frac{\pi}{\beta} - \frac{6\cdot\zeta(3)}{\pi}\frac{1}{\beta^2} + \frac{19\pi^6 - 2160\cdot(\zeta(3))^2}{120\pi^3}\frac{1}{\beta^3} -\right.$$

$$- \frac{1}{20\pi^5}\left(\pi^6\cdot\zeta(3) + 1080\cdot(\zeta(3))^3 + 360\pi^4\cdot\zeta(5)\right)\frac{1}{\beta^4} +$$

$$\left.+ \frac{1}{201600\pi^7}\left(8473\pi^{12} + 1723680\pi^6\cdot(\zeta(3))^2 - 163296000\cdot(\zeta(3))^4 - 21772800\cdot\zeta(3)\cdot\zeta(5)\right)\frac{1}{\beta^5}\right] +$$

$$+ o\left(\frac{1}{\beta^5}\right), \quad (\beta \to \infty)$$

, (4)

where $\zeta(s) = \sum_{n=1}^{+\infty}\frac{1}{n^s}$ — Riemann's zeta-function, and $\gamma = 0,5772157...$ — Euler's constant. Constant of variation of random variable ξ is dimensionless size that allows to use it as a universal quantitative assessment of distribution. All calculations and computer modeling were executed in a professional mathematical Wolfram Mathematica 7.0 package.

Weibull-Gnedenko's distribution allows to capture all life cycle of objects investigated on reliability that does it to one of key distributions in reliability theory [5, etc.]. By results of many pilot studies the typical curve of failure rate usually has an U-shaped appearance, thus allocate three main periods of life cycle: extra earnings (I), normal operation (II) and degradation (III) (*Figure 2*). Weibull-Gnedenko's distribution allows to approximate an experimental curve of failure rate on each of the main periods of functioning of system. In particular, the period extra earnings responds Weibull-Gnedenko's distribution with parameter $\beta \in (0;1)$; the period of normal operation – with parameter $\beta \approx 1$ and the aging period – with parameter $\beta > 2$ (in this case the curve of failure rate is convex down). It follows from research of functional dependence on parameters α and β failure rate $\lambda(t)$, looking like:

$$\lambda(t) = \frac{f(t)}{1 - F(t)} = \alpha^{\beta}\cdot\beta\cdot t^{\beta - 1}. \qquad (5)$$

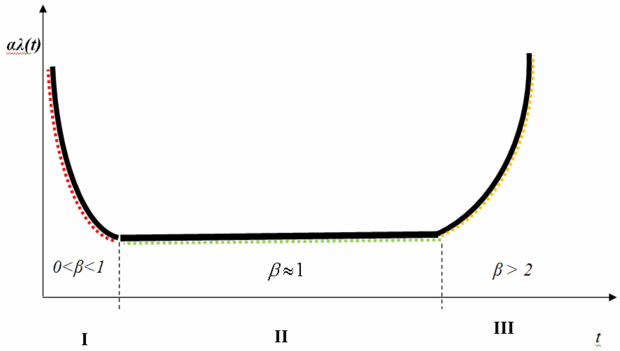

Figure 2. Approximation of curve failure rate by distribution Weibull-Gnedenko (dotted line)

Let's notice that upon transition from II to the III stage value of parameter of a form β changes in steps from 1 to value more than 2.

Let's consider the problem on finding of the moment of the beginning of degradation processes at exploitation of objects of GTS, in particular GCU and SAC GCU that is an actual task for a mode of functioning of active elements of gas transport systems. A condition characterizing the third operational phase of object, to equivalently following inequalities:

$$\beta > 2 \quad \Leftrightarrow \quad \lambda(t) > 2t\alpha^{\beta} \quad \Leftrightarrow \quad \frac{\lambda(t)}{t} > 2\alpha^{\beta}. \qquad (6)$$

At exploitation of objects of GTS, in particular and SAC GCU, it is possible to find the moments of the beginning of degradation processes GCU on the basis of studying of theoretical density of probability of refusal of the equipment, Weibull-Gnedenko subordinated to two-parametrical distribution. The maximum growth of probability of refusal of the equipment corresponds to the first inflection point of function of density of probability of refusal which is more to the left of mean of random variable ξ. Having carried out simple transformations, we will receive a formula for finding of a point of the maximum change of probability of the refusal, the corresponding point of a change of dependence $\lambda(t)$:

$$t_{crit} = \left(\frac{3(\beta - 1) - \sqrt{(\beta - 1)(5\beta - 1)}}{2\alpha\beta}\right)^{\frac{1}{\beta}}. \qquad (7)$$

This expression is defined at values $\beta > 2$. Let's note that in our case $t_{crit} < M\xi$. It is simple to be convinced that

$$t_{crit} < \alpha^{-\frac{1}{\beta}}, \qquad (8)$$

in view of that

$$\lim_{\beta\to\infty}\left(\frac{3(\beta-1)-\sqrt{(\beta-1)(5\beta-1)}}{2\beta}\right)^{\frac{1}{\beta}}=1.$$

Therefore, in failure rate terms, we receive

$$\lambda(t_{crit}) < \beta\cdot\alpha^{\frac{1}{\beta}-2} \qquad (9)$$

So, let there are operational data on refusals of active elements of GTS $\{\tau_k\}, k=1,..,n$. We form sequence $\{t_k\},\ k=1,..,n-1$ where $t_k=\tau_{k+1}-\tau_k$. Assuming that time distribution between refusals submits to Weibull-Gnedenko's two-parametrical distribution with function of distribution (1) we will find dot estimates of unknown parameters α and β. Mean time of no-failure operation, i.e. a time between failures, makes

$$T_1 = M\xi = \frac{1}{\alpha}\Gamma\left(1+\frac{1}{\beta}\right).$$

Therefore, values should t_k to lie in a vicinity of T_1 in the normal operation, being characterized constancy of failure rate. Process of aging (degradation) means failure rate increase (*Figure 3*), intervals between refusals decrease that corresponds to approach t_k to t_{crit}.

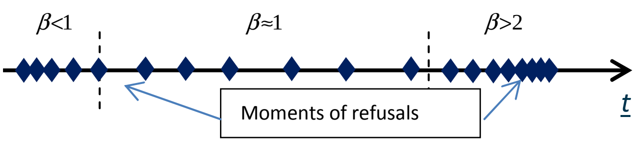

Figure 3. Failure rate depending on duration of operation of the equipment from the point of view of the moments of refusals.

We use a chart-analytic method of finding of estimates of parameters of distribution of Weibull-Gnedenko. At first we receive primary statistical characteristics: selective average $\bar{t}$, selective variance S_t^2, selective constant of variation v_t, empirical function of distribution $F_{cum}(t)$. From a ratio

$$v_t^2=\left(\frac{S_t}{\bar{t}}\right)^2=\frac{\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)}{\Gamma^2\left(1+\frac{1}{\beta}\right)}$$

we receive a preliminary estimate for value of parameter of a shape β.

Let's carry out linearization of function of distribution of Weibull-Gnedenko

$$\ln(-\ln(1-F(t)))=\beta\cdot\ln t-\ln\alpha.$$

The specified ratio allows for finding of other preliminary estimates of parameters of distribution of Weibull -Gnedenko α and β to apply a method of the smallest squares. The device censored [6] quantile regressions is necessary for us. For specification of estimates the traditional method of the maximum likelihood is applicable. In this case the likelihood equations register in a look:

$$\begin{cases}\dfrac{n}{\beta}+\sum\limits_{k=1}^{n}\ln t_k-\dfrac{n}{\sum\limits_{k=1}^{n}t_k^{\beta}}\cdot\sum\limits_{k=1}^{n}t_k^{\beta}\ln t_k=0,\\ \alpha=\dfrac{1}{n}\sum\limits_{k=1}^{n}t_k^{\beta}.\end{cases} \qquad (10)$$

It is possible to prove that the solution of the first equation of system (10) exists and is unique [5]. Using β as initial value for the numerical solution of the nonlinear equation of system (10) relatively β with Mathematica package use, we specify values of parameters of the shape and scale for Weibull - Gnedenko's distribution.

For finding of the look-ahead moment of starting time of degradation processes in the equipment, we use a ratio:

$$t_{crit}=\left(\frac{3(\beta-1)-\sqrt{(\beta-1)(5\beta-1)}}{2\alpha\beta}\right)^{\frac{1}{\beta}}.$$

3. Algorithm of an assessment and forecasting of indicators of reliability of GCU and SAC GCU on the basis of statistical data about refusals

Accumulation of statistical operational information on active elements and its structuring in a uniform database is a necessary condition for carrying out the subsequent mathematical calculations and formation of the analytical conclusions. In trial operation of system in a database data on emergency and compelled stops of active elements and to refusals of their accessories for some years were brought.

The technique of an assessment and forecasting of parameter of a stream of refusals, time between failures and functions of readiness of GCU and SAC GCU is offered. Considering this approach, we will consider that GCU and SAC GCU are restored systems.

The algorithm of an offered technique consists of eight main steps:

Step 1.1. A choice by means of the klasterny analysis of statistical data on GCU and SAC GCU refusals. The user in a dialogue mode is given opportunity by means of the cluster analysis to carry out classification of studied units (or refusals).

Step 1.2. Drawing up by the user of sample of statistical data on GCU and SAC GCU refusals. It is carried out by the user of system manually, taking into account an appropriate filtration and group of operational data.

Step 2. Sample check on existence of emissions by means of a statistical criterion. In case of a deviation from admissible critical value for the chosen operational data, the system allows the user to exclude false statistical data.

Step 3. Sample check on uniformity by means of Kolmogorov-Smirnov criterion. Need of this check is caused by possible belonging of basic operational data to various types of technology equipment and automatic equipment systems, to groups of the refused equipment etc.

Step 4. Creation of schedules of parameter of a stream of refusals $\omega(t)$, time between failures $T(t)$ and readiness functions $K_г(t)$ for statistical data on GCU and SAC GCU refusals.

Step 5. The analysis of the received values of parameter of a stream of refusals $\omega(t)$ on trend existence. Check is carried out by means of calculation and the analysis of value of an indicator of Hurst. In case of lack of a steady trend in a number of values of parameter of a stream of refusals $\omega(t)$ the algorithm of data handling comes to the end.

Step 6. Creation of lines of regression $\Omega(t)$ for values of parameter of a stream of refusals $\omega(t)$ and calculation of merit figures of regression models. The system carries out creation of regression models on the basis of approximating functions of the following look: $\Omega(t) = a + b \cdot t$, $\Omega(t) = a + b \cdot t + c \cdot t^2$, $\Omega(t) = a + b \cdot t + c \cdot t^2 + d \cdot t^3$, $\Omega(t) = e^{a + b \cdot t}$. Creation of lines of regression is carried out by IAS on a classical method of the smallest squares.

Step 7. Definition of optimum regression model. The choice of optimum (most adequate) regression model is carried out by system on the basis of comparison of parameters of adequacy of models (the corrected factor of determination) for the functions received on the previous step.

Step 8. Forecasting of parameter of a stream of refusals $\omega(t)$, time between failures $T(t)$ and readiness functions $K_г(t)$ GCU and SAC GCU on the basis of the chosen optimum regression function $\Omega(t)$, approximating values of parameter of a stream of refusals $\omega(t)$.

Within the analysis two samples of operational data were considered. The first sample contained statistical information on the events which have arisen at a stage extra earnings of units of type of A. Usually, at this stage emergency events have the casual (sudden) character connected with errors of commissioning, factory defects. Thereof, forecasting of indicators of reliability for this stage is not carried out. It is expedient to count dot estimates of indicators of reliability for comparison of operational data with passport characteristics and specifications of active elements.

The second sample was presented by statistical information on the events which have occurred at stages of normal operation and aging (resource development) units of type of B. On the stage of degradation (aging) emergency events are connected with accumulated fatigue, the wear, natural aging of active elements and have gradual character. Forecasting of indicators of reliability of active elements at this stage is of special interest both for the maintaining organizations, and for manufacturers and designers of GCU and SAC GCU.

Further results of the carried-out calculations on an assessment and forecasting of parameter of a stream of refusals are presented $\omega(t)$, time between failures $T(t)$ and readiness functions $K_г(t)$ for the operational data containing in the second sample. In this sample on a period from 65 000 hours to 91 000 hours (time of a "pure" operating time of units) 42 refusals which gave to compelled or emergency stops of 5 maintained units were considered. For units of type B the appointed resource (according to specifications) makes 100 000 hours.

During calculations absence of emissions in considered statistical sample was established. On uniformity initial sample was not checked, as all studied refusals belong to uniform type of the refused elements (refusals of control-measuring devices and automation, the GCU uniform type).

After statistical check of initial sample, calculation of values and creation of schedules of indicators of reliability it is necessary to execute check of the received values of parameter of a stream of refusals $\omega(t)$ on existence of a steady trend. Analysis of value of an indicator of Hurst H for a number of values of parameter of a stream of refusals $\omega(t)$ showed that in a considered number of values of parameter of a stream of refusals $\omega(t)$ there is a steady trend.

As a result of application of a method of the smallest squares for approximation $\omega(t)$ the polynomial of the first degree, polynomial of the second degree, polynomial of the third degree and exponential function received values of estimated factors for considered types of functions. For each of the received regression models values of the corrected factor of determination were calculated. On the basis of the analysis of indicators of adequacy of models approximating function of a look was chosen as the most adequate (optimum) regression curve $\Omega(t) = a + b \cdot t + c \cdot t^2$.

The forecast of values is given till time, in which confidential interval for dot value of a dependent variable of the equation of regression $\Omega(t)$ increases twice in comparison with average value of a confidential interval in a time domain of basic data.

On the basis of the chosen regression model calculation of values of parameter of a stream of refusals is carried out $\omega(t)$, time between failures $T(t)$ and readiness functions $K_г(t)$ for considered time intervals of area of basic data, and also look-ahead estimates of indicators of reliability for an operating time interval from 91 000 hours are received. to 95 200 hours.

By results of the carried-out calculations it is also possible to note the following fact. The value of a time between failures specified in passport data for type B as the minimum value of an average time between failures, is equal 3 500 hours. For the operating time period from 82 600 hours to 91 000 hours, and also for a look-ahead interval, value of a time between failures $T(t)$ it is less than the value of an indicator of reliability specified in passport data of the unit (3 500 hours).

3. Conclusion

1. The urgency and need of creation of information and analytical systems of an assessment and reliability monitoring for GTS is shown.
2. On the basis of research of distribution of Weibull-Gnedenko received formulas for engineering calculation of reliability assessments that is especially important for the period of degradation of life cycle of considered object. Practical application of look-ahead estimates of indicators of reliability in a combination to economic criteria consists in definition of the moment of time after which further operation of growing old active elements becomes economically inefficient owing to high losses because of repairs and idle times of objects. Also look-ahead estimates of function of readiness of objects can be used for planning of gas deliveries and carrying capacity of gas pipelines.
3. The algorithm of an assessment and forecasting of indicators of reliability of active components of GTS is constructed. The statisticians received on the basis of processing about assessment refusals essentially differ from the passport.
4. Existence in system of an assessment and monitoring of reliability of analytical information on refusals and a technical status of active elements allows to provide feedback with producers and designers for the purpose of correction of specifications and passport data of technology equipment and management systems.
5. The offered integrated approach to reliability augmentation of functioning of technology equipment allowed to automate a part of functions within consolidation of data on refusals of technology equipment and provided possibility of an assessment of functioning on a technical status of the equipment.

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