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DIAGNOSTICS OF FUNCTIONAL RELIABILITY OF PIPELINE SYSTEMS

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Analytical models of diagnostics of functional reliability of pipeline systems are formulated in the work. They can be used in the design of an automated system for diagnosing the reliability of pipeline systems (ASDR), which provides a single information space for timely and coordinated support for management decisions in the workplace of technicians and repair personnel of structural units of the pipeline system. The problem of cost minimization is formulated, which is solved by numerical optimization methods and graphical method. ASDR allows to carry out the comparative analysis of alternative structures of a pipeline network on criterion of functional reliability.

Introduction

For all actors involved in the pipeline system, the problem of reliability is controversial. Thus, producers and consumers of the target product, on the one hand, want the pipeline system to be reliable, and on the other - that transport services are cheap. Operators, on the one hand, seek to ensure the reliability of the system in the future at the appropriate level, and on the other - to allocate as little financial, material and labor resources to achieve and maintain this level.

Conflict resolution can only be achieved by finding a compromise value of current reliability that would satisfy all subjects of the system equally. The compromise value must not be lower than the minimum value stipulated by all parties in bilateral contractual obligations. However, the deviation from the minimum allowable value in the direction of increase should be insignificant, because the increase in reliability for existing systems, even at one hundredth of a percent, is associated with high resource costs. Therefore, among the reliability indicators we can distinguish two main ones that affect the functioning of the pipeline system and which we call functional reliability [1]:

– maintainability, which determines the property of the system to continuously transport the target product to consumers during maintenance work in order to restore the technical reliability of structural elements of the system, which they lose during long-term operation due to wear or aging;

– the probability of uninterrupted supply of the target product to a particular consumer or group of consumers over a period of time, which determines the objective ability of the system to meet its purpose [2]. Improving the functional reliability of pipeline systems (PS) is one of the most important tasks facing operators and in which all stakeholders of the transportation system are interested.

The reliability of PS is set at the design stage and maintained at the stage of construction and commissioning. However, over time, the reliability of individual structural elements decreases, which leads to the need for rapid diagnosis of the reliability of PS in order to make appropriate management decisions and measures to maintain reliability at a given level.

This can be realized only by developing a diagnostic system that collects data on the state of individual elements of PS and the calculation of functional reliability, using appropriate methods and models. In general, such a system will be a subsystem of the automated dispatcher control system of the entire PS.

Main part

In the general case, the automated system of reliability diagnostics (ASDR) should be a subsystem of the automated process control system of the whole PS [3]. The main purpose of creating ASDR is:

– monitoring and forecasting the technical condition of the pipeline as a whole and its elements;

– monitoring of the resource of the pipeline and tank farms;

– planning and control of current, medium and capital repairs.

The actual basis for the implementation of ASDR is the executive documentation; factory catalogs and technical passports of the equipment; retrospective statistical material; experience in operating the existing pipeline;

information coming from control sensors installed at critical points of the pipeline network.

ASDR is designed to provide a single information space for timely and coordinated support for management decisions in the workplaces of technicians and repair personnel of structural units of the PS.

Since the automated process control system PS is generally a multi-level system, the functional structure of ASDR is considered as a system to support management decisions at each level of management.

It includes the implementation of a sequence of the following steps: data entry; data analysis; Data Processing; development and selection of optimal plans; performance control.

For the successful operation ASDR requires operational monitoring of the PS, timely detection of critical areas and emergency areas, maintenance and repair work [4]. These works are performed by emergency crews. Therefore, the task of calculating their optimal number arises. Since applications for repair work are received at random times, to perform the task of calculating the optimal number of repair crews, it is necessary to involve mathematical methods of queuing theory.

From the database "Prehistory" it is possible to estimate intensity of receipt of requests for a call of repair crews λ and average time of elimination of the next accident τ. Let the number of repair crews be n. Then the process of eliminating emergencies on the pipeline system can be described by a multi-line queuing system. The total flow of applications for maintenance of the pipeline system at the entrance of a specialized organization is formed as a superposition of many flows for maintenance from buildings. Therefore, according to the queuing theory [5] it is Poisson (simpler), in which the probability that during the τ time will arrive exactly k queries is described by the Poisson formula $P_k(\tau) = \frac{(\lambda\tau)^k}{k!} e^{-\lambda\tau}$, and the distribution of time between the arrival of neighboring applications is exponential with the distribution function $A(t) = 1 - \exp(-\lambda t)$. The distribution of the time of liquidation of pipeline accidents can also be chosen exponential with the distribution function $B(t) = 1 - \exp(-\mu t)$, where $\mu = 1/\tau$ is the intensity of service requests. With the exponential distribution law, the whole system will rely on the most difficult mode of operation [6].

That is, we obtained the so-called Markov multilinear queuing system, the study of which was conducted in [7]. If we denote the workload of one team by $\rho = \lambda / \mu$, then its main characteristics of the developed model are as follows:

– the probability that all crews are free:

$$p_0 = \left[\sum_{i=0}^{n-1} \frac{\rho^i}{i!} + \frac{\rho^n}{(n-1)!(n-\rho)} \right]^{-1} \tag{1}$$

at $\rho/n < 1$;

– the probability that all crews are busy and there are no queues for service is:

$$p_n = \frac{\rho^n}{n!} \cdot \left[\sum_{i=0}^{n-1} \frac{\rho^i}{i!} + \frac{\rho^n}{n(1-\rho/n)(n-1)!} \right]^{-1}, \ \frac{\rho}{n} < 1. \tag{2}$$

The average waiting time for a request to start service is:

$$T_q = \frac{p_n}{\mu n(1-\rho/n)}, \ \frac{\rho}{n} < 1. \tag{3}$$

Accordingly, the load factor of teams to service requests (as a percentage) can be represented as:

$$k_z = \left(1 - \frac{1}{n} \sum_{i=0}^{n-1} \frac{n-i}{i!} \rho^n \cdot \left[\sum_{i=0}^{n-1} \frac{\rho^i}{i!} + \frac{\rho^n}{n(1-\rho/n)(n-1)!} \right]^{-1} \right) \cdot 100\% . \tag{4}$$

Now, having the basic indicators of system, it is possible to carry out tasks concerning optimum service of requests for a call of repair crews.

From the standpoint of a specialized organization that serves PS, you need to minimize costs, while adhering to certain restrictions, namely: the deviation of the actual time of repair from the normative should not exceed the value T_{kr}, and all requests to eliminate accidents must be fulfilled. This means that the organization has a certain margin of capacity to service emergency calls.

It is possible to minimize costs within the developed model only due to the number of teams n_m, aiming at their maximum load. So, we have a mathematical programming problem that looks like: to find n_m, which maximizes the function k_z when the constraints $T_q < T_{kr}$ and $\lambda / (n\mu) < 1$ are met.

It is possible to formulate a problem differently: to find n_m which minimizes function T_q at performance of restrictions $k_z > k_{\min}$ and $\lambda / (n\mu) < 1$ where $k_{\min}$ is the minimum level of loading of crews on service of accidents on PS. Both problems can be solved by numerical optimization methods.

Given the low accuracy of approximation of the laws of distribution, the tasks can be solved graphically. Fig. 1 shows graphs of the start time of the repair request (in hours) depending on the number of repair crews and the load per crew, with a normal repair time of 10 hours.

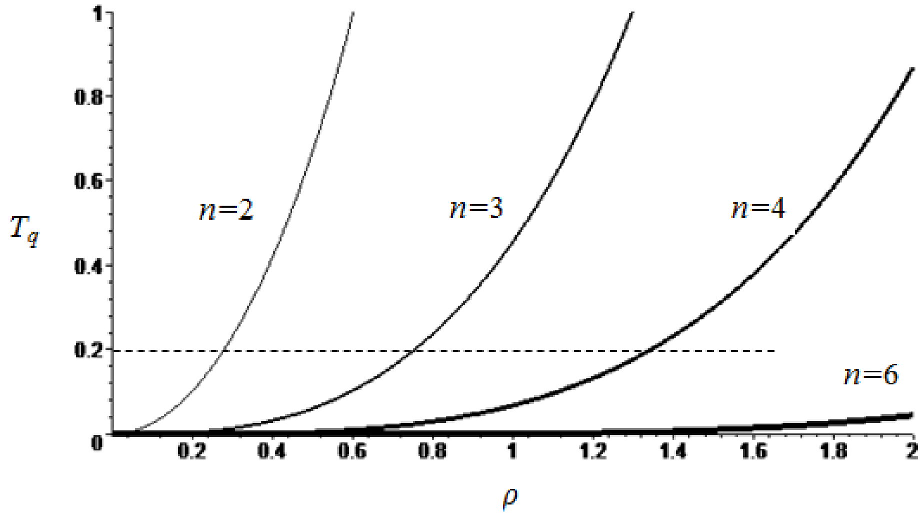

Fig. 1. Graphs of delay time of the beginning of repair

By setting the load per team and the minimum delay time, you can find the desired number of teams on the charts. So, with a delay time of 0.2 time and a workload of 0.8, the minimum number of teams is three.

The development of the system of functional reliability diagnostics is based on the division of PS into emergency repair zones and replacement of the PS structure by the macrostructure of emergency repair zones (ERZ), which completely inherits the functional reliability of the system. For this reason, in the future this analytical method of calculating the functional reliability of PS will be called the ERZ method. Let's consider its main provisions.

The ERZ method consists of seven consecutive steps [8]:

1. Formation of a mathematical model of a pipeline transport network with a complex topological structure in the form of a weighted graph.

2. Dividing the initial weighted graph of the pipeline network into subgraphs (macroelements), each of which corresponds to one ERZ.

3. Calculation of technical reliability of ERZ as an independent macroelement in the operation of PS.

4. Converting the initial weighted graph of a large-dimension network to a weighted macrograph ERZ of small-dimension (replacing the micrograph of each ERZ with a single vertex).

5. Construction of a simplified ERZ macrograph in relation to a specific consumer of the pipeline network.

6. Construction of a calculation model of the functional reliability of the pipeline network for a specific consumer.

7. Formation of a mathematical model of functional reliability of the network relative to a particular consumer using the classical methods of the theory of reliability of technical systems and direct calculation of functional reliability.

A mathematical model is formed for each consumer $\mathbf{O}_{\text{Сп}k}$ of the pipeline system $k \in \left\{\overline{1, K}\right\}$ [9]. Here K is the total number of consumers. If several consumers receive the target product from only one zone, then the corresponding mathematical models of functional reliability coincide.

The following initial data are used to form a mathematical model of functional reliability in relation to the consumer $\mathbf{O}_{\text{Сп}k}$:

– calculation model of functional reliability in relation to the consumer $\mathbf{O}_{\text{Сп}k}$;

– weight function p at the vertices of the ERZ graph, which determines the technical reliability of each ERZ network;

– weight function p_a on the edges of the graph ERZ, which determines the technical reliability of the shut-off valves of the network.

If the calculated model of functional reliability for an arbitrary consumer $\mathbf{O}_{\text{Сп}k}$ consists only of series-connected and parallel-connected elements (no bridge connections), then the process of forming a mathematical model corresponds to the algorithm shown in fig. 2.

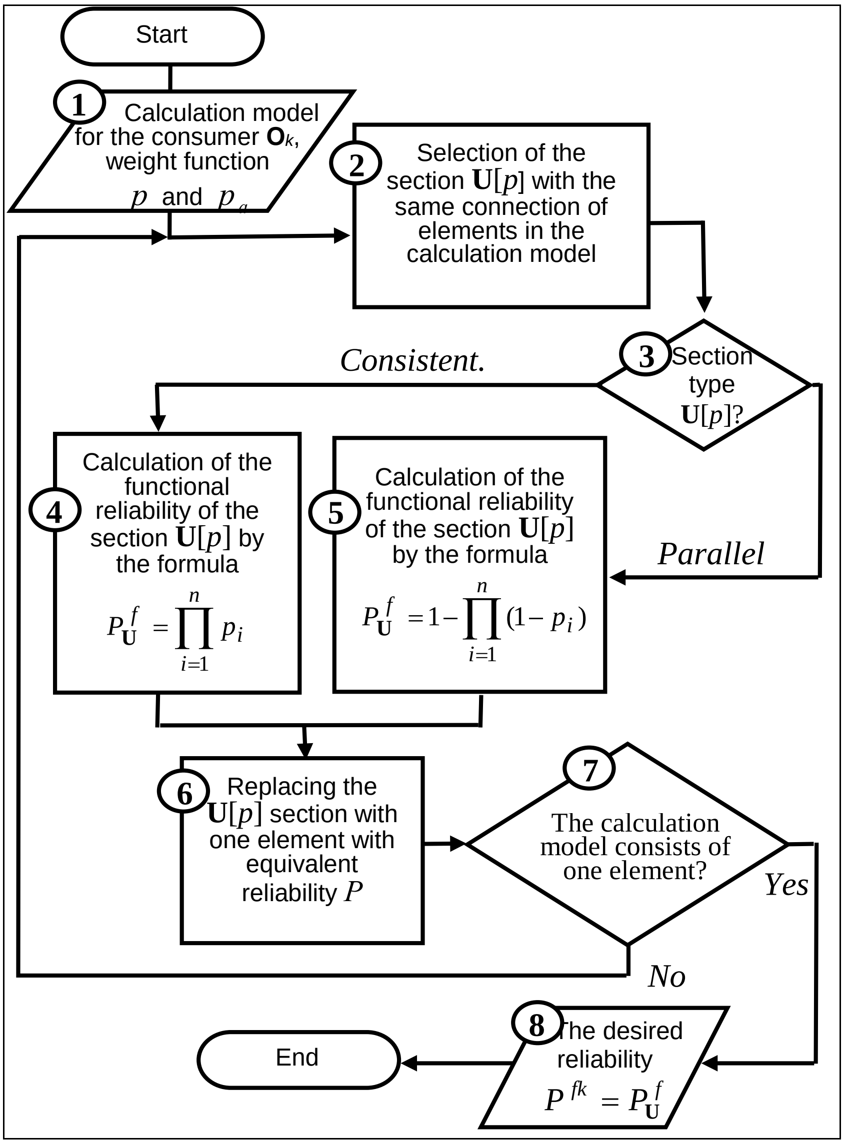

Fig. 2. Scheme of the algorithm for building a mathematical model of functional reliability of the network in relation to a particular consumer

As follows from the algorithm, the formation of a mathematical model of the functional reliability of the network in relation to the consumer $\mathbf{O}_{\text{Сп}k}$ is a cyclical process of replacement in the calculation model of sections $\mathbf{U}[p]$ with the same connection of elements by one element with equivalent reliability.

Equivalent reliability is calculated by the formula $P_{\mathrm{U}}^{f}=\prod_{i=1}^{n}p_i$ (in the case of series connection of elements) or by the formula $P_{\mathrm{U}}^{f}=1-\prod_{i=1}^{n}(1-p_i)$ (in the case of parallel connection of elements). Here n is the number of elements in the same type of fragment; p_i - the probability of trouble-free operation of the element of the pipeline network corresponding to the i-th element of the fragment. The value p_i is selected according to the weight functions p and p_a of the ERZ graph.

The cyclic replacement process continues until the computational model consists of only one element. The calculated formula P_{U}^{f} for the reliability of this element will be the desired mathematical model of the functional reliability of the network in relation to the *k*-th consumer of the system [10]:

$$P_k^f = P_{\mathrm{U}}^f, \quad k=\overline{1,K}. \tag{5}$$

The value P_k^f indicates the probability that the pipeline network provides the target product from the source to the *k*-th consumer of the system for a certain period of time (usually one year).

Under this example, the initial data are as follows:

– calculation models of functional reliability, which are determined in the previous stages;

– weight function p on the vertices of the graph ERZ;

– weight function p_a on the edges of the graph ERZ.

The work of the algorithm for constructing mathematical models in the example gives the following results (generated mathematical models):

– relating the first consumer $\mathbf{O}_{\text{Сп}1}$:

$$P_1^f = p_{a1} p_{a2} \times$$
$$\times [1-(1-p_1 p_{a3} p_3 p_{a5} p_5 p_{a7} p_{a9} p_8 p_{a16} p_{a11} p_{10} p_{a19} p_{a13} p_9 p_{a18} p_{a12} p_7 p_{a15}) \times$$
$$\times (1-p_2 p_{a4} p_4 p_{a8} p_{a7} p_6 p_{a14})] \, p_{a10}\,; \qquad (6)$$

– relating the second consumer $\mathbf{O}_{\text{Сп}2}$:

$$P_2^f = p_{a1} p_{a2} [1-(1-p_1 p_{a3} p_3 p_{a5} p_{a6})(1-p_2 p_{a4} p_4 p_{a8} p_{a7})]; \qquad (7)$$

– relating the third consumer $\mathbf{O}_{\text{Сп}3}$:

$$P_3^f = p_{a1} p_{a2} [1-(1-p_1 p_{a3} p_3 p_{a5} p_{a6} p_5 p_{a17} p_{a11} p_{10} p_{a19} p_{a9} p_8 p_{a16}) \times$$
$$\times (1-p_2 p_{a4} p_4 p_{a7} p_{a8} p_6 p_{a14} p_{a10} p_7 p_{a15} p_{a12} p_9 p_{a18})] \, p_{a13}\,; \qquad (8)$$

– relating the fourth consumer $\mathbf{O}_{\text{Сп}4}$

$$P_4^f = p_{a1} p_{a2} [1-(1-p_1 p_{a3} p_3 p_{a6} p_{a5} p_5 p_{a17}) \times$$
$$\times (1-p_2 p_{a4} p_4 p_{a7} p_{a8} p_6 p_{a14} p_{a10} p_7 p_{a15} p_{a12} p_9 p_{a18} p_{a13} p_{10} p_{a19} p_{a11} p_8 p_{a16})] p_{a9}\,, \qquad (9)$$

where $p_{a1}, p_{a2}, \ldots, p_{a19}$ – the value of the weight function p_a; $p_1, p_2, \ldots, p_{10}$ – the value of the weight function p.

Calculations of functional reliability by mathematical models (6) - (9) in the example give the following values: $P_1^f = 0{,}935\,1$; $P_2^f = 0{,}975\,6$; $P_3^f = 0{,}923\,2$; $P_4^f = 0{,}931\,6$.

Conclusions

The obtained mathematical models can be used not only to calculate the specific value of the indicator of functional reliability, but also to analyze them in order to further improve the design of the network. Only the general appearance of the model can lead to conclusions about the feasibility of new changes in the structure of the network. Thus, all models (6) - (9) show a weak point in the design of the network associated with the latches a_1 and a_2. If the failure of any section does not lead to the cessation of transportation of the target product to at least one consumer, the failure of the latch a_1 or a_2 leads to a general cessation of transportation of the target product in the network. According to model (6), if the latch a_{10} fails, the transportation of the target product to the consumer $\mathbf{O}_1$ (and only to him) becomes impossible. Similarly, models (8) and (9) indicate that failure of the latch a_{13} or a_9, leads to the cessation of transportation of the target product accordingly to the consumer $\mathbf{O}_3$ or $\mathbf{O}_4$.

Therefore, the analysis of only the type of models (6) - (9) leads to the conclusion that it is necessary to preserve the latches a_1 and a_2, as well as the desired reservation of latches a_9, a_{10} and a_{13}. In the latter case, to correct the situation, it is enough to attach to each latch in series another, the same.

The PS system reliability diagnostics system and the ERZ method in particular bring the greatest benefit to the design of new PS, which allows for a comparative analysis of alternative structures of the pipeline network on the criterion of functional reliability.

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