Management of the Technical System Operation Based on Forecasting its “Aging”

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Abstract. The subject of the research is the models and mechanisms of operation of technical systems. The purpose of the paper is to develop a model for managing the technical system operation based on the forecasting its “aging”. The following tasks are solved in the article: determination of the failure modes and effects of technical systems; building a model for managing the technical system in order to forecast the development of malfunctions and the appearance of failures of its elements; development of a system for managing the risk of failures of the technical system elements based on the method of Failure Modes Effects Criticality Analysis; determination of the technical system bifurcation points. The following results were obtained: on the basis of graph theory, a conceptual model for managing the technical system was developed, which serves as a basis for forecasting its operation; the matrix of failure of the technical system elements is built on the basis of the ranking system for evaluating parameters and determining the severity of the failure effects for the technical system elements; a risk management system for the failure of the technical system elements was developed based on the method of Failure Modes Effects Criticality Analysis. The points of bifurcation of the technical system were determined, that is, the points in time when it is necessary to analyze the technical system progress and decide on the advisability of stopping the system and conducting maintenance and repair of its elements.

Keywords: Technical System, Forecasting, Risk Management.

1 Introduction

Improving the efficiency of using technical systems at the present stage is impossible without constant monitoring of their condition and forecasting the development of malfunctions during operation.

The full cycle of monitoring the state of technical systems includes the following

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steps: detecting deviations in the technical system; identification of malfunctions and their causes; forecasting the development of malfunctions; adoption of recommendations for corrective actions; analysis of the state after stopping the technical system. Obviously, forecasting the state of technical systems is an important action, the results of which will later help diagnose the operability of the technical system and identify the risks of its failure. To forecast the development of the malfunction, knowledge of the possible failure modes for machines of this mode and thorough understanding of the relationships between the operating states of technical systems and failure modes are required. The forecasting should include the application of analytical models of origin and development of damage in the technical system [1]. Failure Modes Effects Criticality Analysis (FMECA) is a systematic analysis method to identify possible failures, their causes and effects, as well as the impact on the functioning of a system (system as a whole or its components and processes) [2]. Failures in the technical system are determined by controlled parameters. The general forecasting procedure includes the following main points: determining the end point (usually the stopping point of the technical system); observation of parameter changes and assessment of the speed of the technical system development; determination of the current technical condition; obtaining an estimate of the time to failure or the technical system residual resource; setting the horizon for forecasting events.

2 Analysis of Literature Data and Resolving the Problem

In the development, design and creation of complex technical systems, knowledge of the quantitative and qualitative laws inherent in the objects under consideration is required. In connection with the large expenses of finance and time that are necessary to establish these regularities experimentally, the use of mathematical modeling methods to study the system properties is becoming increasingly important [3, 4].

The form and structure of the presentation of the technical system depend on the nature of the processes occurring in it and external factors, on the nature of the quantitative relationships between parameters and characteristics, as well as on which aspects of the process and factors are put forward in relation to a specific goal, means and methods of research [5-7]. To control the operation of technical systems on the basis of forecasting their “aging”, the studied elements are distinguished as characteristic generating the technical system couplings. External technological, technical and economic relations are replaced by their generalized description or quantitative characteristics [8-10]. The forecast is an estimate of the time to failure and the probability of a single or multiple failure due to malfunctions (damage) that occur at the moment or are expected in the future [11, 12]. The effectiveness of the forecast depends on how well the modes of malfunctions and failures for a technical system of this mode are known and described by the model, how they depend on the service life and project of a particular technical system, how they develop over time [13, 14]. The forecast is based on experience-proven knowledge about the development processes of various modes of malfunctions [15, 16]. The forecast makes it possible to evaluate the technical system residual life with a sufficient degree of certainty to make a decision that helps prevent a possible failure, take corrective actions to extend the technical system life, or use the available time reserve to prepare for an impending failure [17].

Failure Modes Effects Criticality Analysis – FMECA is applicable at various levels of the technical system decomposition, that is, from the system as a whole to the functions of individual components or software commands [2]. The definition of criticality implies the use of a qualitative measure of the failure modes effects [18, 19]. Therefore, it can be stated that FMECA is a method that allows identifying the severity of the potential failures modes effects and provide measures to reduce risk and assess the probability of the technical system failure modes [20].

3 The Purpose and Objectives of the Research

The purpose of this article is to increase the efficiency of the use of technical systems by improving control procedures and predicting their condition during operation.

The objectives of this research: to determine the failure modes and effects of technical systems; to build a model for managing the technical system in order to forecast the development of malfunctions and the appearance of failures of its elements; to develop a system for identifying, analyzing and managing the risks of failures of the technical system elements based on the method of Failure Modes Effects Criticality Analysis FMECA; to determine the bifurcation points of the technical system.

4 Materials and Methods of the Research

The technical system is considered as a single complex of heterogeneous elements, designed to generate energy through the simultaneous continuous implementation of various interconnected processes of a real cycle. Any change in a parameter or element of the technical system to one degree or another affects the parameters, characteristics and indicators of the whole complex. This influence for each individual k-th element is transmitted through the combination of its boundary (input and output) parameters Z_k, which determine the direction and nature of the processes in the technical system elements and at the same time play a connecting role between them. The set of values of such coupling parameters completely determines the technical system operational state as a whole and its individual elements. The technical system is modeled as a uniform system of elements with connections between them and complexes of external objects. Each element of the technical system is designed to carry out a directed technological process or its separate stage according to certain laws of its stationary course.

It is legitimate to accept that all processes in the technical system elements with one or another permissible stationary load occur continuously. Such processes are connected by stationary flows in accordance with a given coupling circuit. The term "flow" is used hereinafter for various heat transfer mediums and working fluids, through which processes are carried out in the technical system elements and coupling (fuel, air, combustion products, feed water, condensate, steam, plasma, etc.). It is assumed that coupling on the transmission of mechanical and electrical energy is also carried out by appropriate flows. Each stationary coupling has a strictly defined direction corresponding to the actual direction of flow between the technical system elements. Imagine a conceptual model for managing a technical system (Fig. 1).

In recent decades, graph theory has been widely and successfully used to analyze a number of complex systems [14, 15]. A graph is a collection of segments of arbitrary length and shape, called arcs, and intersection points of arcs, called vertices. The main topological information contained in the graph is a graphical expression of the relationships between the vertices of the graph. The positive aspects of this method can be used to solve this problem, since the technological scheme of any real technical system is equivalent in its topological structure to a certain graph. Presentation of the technical system diagram in the form of a graph will make it possible to carry out mathematically rigorous and at the same time sufficiently clear examination of it.

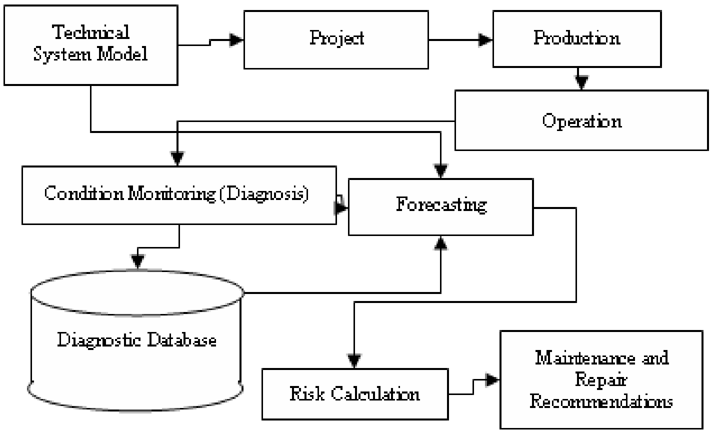

Fig. 1. Conceptual model of the technical system management

A system of elements and relationships modeling a technical system can be represented in the form of a graph in which each element of the technical system corresponds to a vertex of the graph, and the connection between the technical system elements or to external objects is the arc of the graph.

Some adjacent peaks can be connected not by one, but by several opposite or equally directed arcs. This case reflects the presence of several connections made using different flows. Any scheme can be specified in the form of a matrix of connections of the vertices of the graph, supplemented by a matrix of types of connections along the flows of the technical system.

The equations for the entire technical system and its external relations, related to the same period of time, have the following form:

- energy balance equation for each k-th element of the technical system:

$$\sum_{k=1}^{K} E_k = 0 \quad \forall\ k = 1,\dots,K; \tag{1}$$

- the equation of the balance of costs for each l-th flow of the k-th element of the technical system:

$$\sum_{l=1}^{L} G_l = 0, \quad \forall\ l = 1,\dots,L, \tag{2}$$

where G – flow discharge;

- the equation of the hydraulic (aerodynamic) balance for each l-th flow of the k-th element of the technical system:

$$\left(p^{'} \mp \Delta p - p^{''}\right)_{kl} = 0, \tag{3}$$

where p – flow parameter for output (') or input (") coupling of the technical system element; Δp – characteristics of the change in the parameter of the processes in technical system elements.

Between the parameters and technological characteristics of the individual technical system elements there are complex dependencies of various kinds. The establishment of these dependencies is the task of the joint thermal, hydraulic, aerodynamic and strength calculation of elements. The main characteristics for the technical system are:

- characteristics of the change in the parameters of each l-th flow in each k-th element of the technical system:

$$\Delta p_{kl} = \Delta p_{kl}\left(Z_k, Z_k^K\right), \tag{4}$$

where Z_k – set of coupling parameters of the k-th element of the technical system; Z^K – project parameters of the technical system;

- characteristics of the average speed of the l-th flow of the technical system in each k-th element of the technical system:

$$W_{kl} = W_l\left(Z_k, Z_k^K\right); \tag{5}$$

- characteristics of the highest wall temperature for each q-th structural part of each k-th element of the technical system made of a material of the form m:

$$t_{qmk} = t_{qm}\left(Z_k, Z_k^K\right); \tag{6}$$

- characteristics of the absolute or relative wall thickness of each q-th structural part of each k-th element of the technical system made of material m:

$$\beta_{qmk} = \beta_{qm}\left(Z_k, Z_k^K\right); \tag{7}$$

- consumption characteristics of metals and other m-x materials for each q-th part in each k-th element of the technical system:

$$G_{qmk} = G_{qm}\left(Z_k, Z_k^K\right). \quad (8)$$

The influence of the remaining parameters of the technical system Z and Z^K, not related to this k-th element of the technical system, on the characteristics of this element is manifested implicitly through their relationship with the parameters of this element of the technical system. Expressions of characteristics take into account the operating conditions of the technical system at both nominal and partial loads.

The thermodynamic, consumable, and structural parameters of the technical system Z and Z^K cannot take completely arbitrary values, but can only vary within the limits of physically possible and technically feasible states of the technical system, as well as within the limits of technically acceptable initial and operational states of materials in equipment elements. The indicated limitations for various elements of equipment, materials, and energy carriers can be reflected in the form of inequalities in the sets of parameters:

$$Z^{*} \leq Z \leq Z^{**}, \; Z^{K^*} \leq Z^K \leq Z^{K^{**}}, \quad (9)$$

where the indices “*” and “**” refer to the minimum and maximum accepted values of the parameters.

For the given modes and materials of the technical system elements or their structural parts, limiting conditions are imposed on the characteristics of the form (5) – (7), reflecting the requirements of manufacturability and long-term reliable operation of the technical system. These limiting conditions can be represented as follows:

$$W_{kl}^{*} \leq W_l\left(Z_k, Z_k^K\right) \leq W_{kl}^{**}; \; t_{qmk}^{*} \leq t_{qm}\left(Z_k, Z_k^K\right) \leq t_{qmk}^{**}; \; \beta_{qkm}^{*} \leq \beta_{qm}\left(Z_k, Z_k^K\right) \leq \beta_{qmk}^{**}. \quad (10)$$

During the technical system operation, parameters (1) – (8) change, while the system "becomes old". The specified parameters are determined during the diagnosis.

Determination of the influencing factors (causes) of a technical system failure implies finding the parameters on which the rate of development of the technical system malfunction depends (Fig. 2).

Each influencing factor can be considered as one of the driving forces for the development of an existing fault of a specific mode, but it also affects the development of other faults and the emergence of the future technical system failures.

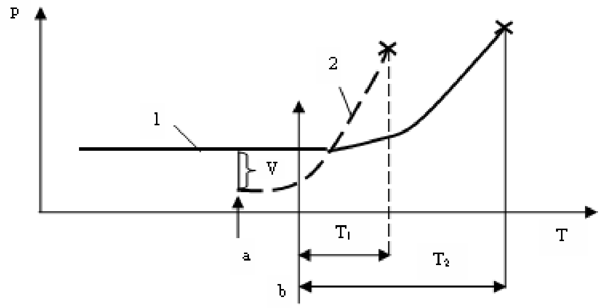

Fig.2. Influencing technical system failure: T – time; p – controlled parameter; 1 – primary failure; 2 – secondary failure; V – influencing factor; T_2 – estimation of time to the primary failure; T_2 – estimation of time to the secondary failure; a – initiation of the secondary failure; b – running time

The failure point for the monitored parameter is the value of the parameter, upon reaching which the object fails. This point is usually determined based on the experience of previous failure observations. The technical system stop level for the same parameter, upon reaching which it is stopped, lies below the point of failure and is used to indicate a failure and to carry out maintenance and repair. Since this level is below the point of failure, its achievement does not yet indicate the technical system complete failure, which makes it possible to avoid destructive damage.

The warning levels are set below the stop level of the technical system elements, based on the reserve of time during which it will be possible to carry out maintenance and repair of the system. The forecasting procedure requires knowledge of the behavior of a set of controlled parameters during the development of a malfunction of a given mode under given operating conditions.

To forecast future failures of a technical system, first of all, it is necessary to determine the criteria for their occurrence through influencing factors, taking into account that the same parameter can serve as an influencing factor for an upcoming failure and be used as a sign of a malfunction leading to a future failure. In this case, the main reason for the failure of this mode can be determined through a set of parameters whose values directly or indirectly indicate the degree of the malfunction development. The result of forecasting is the technical system element malfunction probability within a given period of time. Currently, to reduce the probability of an unfavorable result and minimize possible costs, a risk management methodology is often used, which allows for reliable operation and stable development of the researched system. In general, risk management is an economic concept that implies an iterative process that helps organizations determine a strategy, achieve goals and make informed decisions, contributing to the improvement of the management system. However, the peculiarity of risk analysis is that it considers potentially negative consequences that can also arise as a result of failures in technical systems or failures in technological processes. The main element of risk analysis is hazard identification (detection of possible violations) that can lead to negative consequences. Risk assessment for a technical system includes frequency and impact analysis. However, when the consequences are insignificant and the frequency is extremely small, it is enough to evaluate one parameter. The risk for a technical system is the product of the probability of a particular malfunction on the effects of a malfunction in the technical system. Identification of the technical system risk failure and, if necessary, maintenance and repair affect the performance of the system. Actions should be aimed at identifying and mitigating the effects of failure risks using risk management methods.

The risk of failure in a technical system can be determined as follows:

$$R = P_k \cdot Z_k , \qquad (11)$$

where P_k – probability of failure of the technical system k-th element; Z_k – the degree of impact of the k-th element failure on the technical system, that is, an indicator of the severity of the effects.

If $P_k < 0.2$, then:

$$P_k = 1 - e^{-H_i} , \tag{12}$$

where H_k –failure criticality level of the k-th element for a technical system

The priority value of the risk of failure in the technical system is determined taking into account the level of failure detection of the k-th element G_k of the technical system:

$$RPN = Z_k \cdot U_k \cdot G_k , \tag{13}$$

where U_k – the probability of failure of the technical system k-th element for a given period of time.

Determining the level of failure detection of the technical system k-th element is an assessment of the chance to identify and eliminate the failure of the k-th element by performing maintenance and repair before the effects for the technical system. The values of G are ranked in reverse order with respect to the failure probability or the failure severity. The higher the G value, the less probable failure detection. A lower detection probability corresponds to a higher RPN and higher priority for the technical system failure mode.

By analogy with the FMECA method, a risk matrix is constructed (Table 1).

Table 1. Matrix of the risk of technical system elements failure

Failure probability	Failure rate	Severity of effects		
		Catastrophic effect (3)	Critical effect (2)	Slight effect (1)
(A) – Improbable	$<10^{-6}$	Work	Work	Work
(B)– Implausible	$10^{-4} – 10^{-6}$	Work & Support	Work	Work
(C) – Unlikely	$10^{-2} – 10^{-4}$	Work & Support	Work & Support	Work
(D) – Random	$10^{-1} – 10^{-2}$	Stop	Work & Support	Work & Support
(E) – Probable	$1 – 10^{-1}$	Stop	Stop	Work & Support
(F) – Frequent	>1	Stop	Stop	Stop

In order to determine the points of failure of the technical system elements to prevent the occurrence of the failure risk, the ranking system for evaluating parameters is introduced. The following classification of countermeasures (warning) of situations of failure risk of the technical system elements is used: Stop – stopping the technical system; Work & Support – continued operation of the technical system with maintenance (repair, replacement) of system elements; Work – continued operation of the technical system, if necessary, minor repairs. The severity of the failure effects for the technical system elements is determined as follows: catastrophic failure effects provide for the risk of termination of the primary functions of the technical system elements and cause severe damage to the system, environment and human resources; critical failure effects provide for the risk of termination of the primary functions of the technical system elements and cause significant damage to the system and the environment, but is not a serious threat to human resources; minor failure effects provide for the risk of deterioration in the performance of the functions of the technical system elements without noticeable damage or lack of damage to the system or threat to human resources. The frequency or probability of each mode of failure should be determined to assess the effects or criticality of the failures. The criticality value is associated with the conditional failure rate and operating time and can be used to obtain a more realistic risk assessment corresponding to a specific failure mode during a given operating time of the technical system. The intensity of the i-th technical system failure is estimated using the formula:

$$\mu_i = \omega_k \cdot \lambda_i \cdot \alpha_i \,, \tag{14}$$

where ω_k – failure rate of the technical system k-th element; λ_i – the ratio of the number of the technical system i-th failure to the total number of failure modes; α_i – conditional probability of the technical system i-th failure effect.

The criticality value for the k-th element of the technical system having n failure modes is determined by the formula:

$$H_k = \sum_{i=1}^{n} \omega_k \cdot \lambda_i \cdot \alpha_i \cdot T_k \,, \tag{15}$$

where T_k – active time of the technical system k-th element.

The criticality value is a measure of the technical system failure risk.

Upon reaching or exceeding the values of the technical system monitored parameters established as a criterion for the initiation of a malfunction, a warning signal is triggered to begin the development of a malfunction of this mode. This step serves as the basis for developing recommendations for the maintenance and repair of the technical system defective element. Within the framework of FMECA during the technical system operation, it is possible to determine the points of its bifurcation, that is, time points when it is necessary to analyze the progress of the technical system and decide on the feasibility of stopping the system and performing maintenance and repair of its elements (Fig. 3).

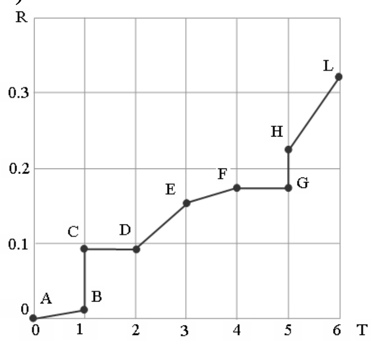

Fig. 3. Technical system bifurcation points: R – risk level; T – technical system operating time; A, B, C, D, E, F, G, H, L – bifurcation points

The value of the initial failure risk of the technical system elements is taken as A. The severity of the effects at the initial stage is Z_0. At a certain point in time of the passage of the AB stream during diagnosis, it was found that the risk level affects the value of Z with the probability of failure P of the technical system element. In such a situation, a decision is made to suspend the technical system operation and to carry out maintenance and repairs at bifurcation point B. As can be seen from the graph, as a result of the element maintenance and start-up, the risk of its failure at time T = 1 rises to point C. In this case, the severity of the technical system element failure effects is Z_1. After applying the risk management system based on the FMECA method, the technical system continues to work with the transition from stage C to stage D with the severity of effects Z_2. At the same time, the risk of element failure does not change, since timely repair and maintenance of the technical system element was carried out. Continuing the technical system operation at the stages DE – EF – FG, at some point in time there is a certain probability of the occurrence of a risk situation of the technical system element failure. The technical system element continues to function with an increased risk level at stage GH. That is, the failure risk increases. Next, transition to stage HL takes place. At point L, the failure risk is maximal for a given period of operation of the technical system. Points A, B, C, D, E, F, G, H, L are bifurcation points, which can be called decision points on the need for maintenance or repair of the technical system elements, taking into account the risk situation. Moreover, for each bifurcation point at certain points in time, it is necessary to build a separate risk matrix for the technical system element failure. With increasing the technical system operating time, the risk of failure of its elements increases. Also, due to the presence of many elements in the system, such matrices are also constructed for each element separately. Combining the results of these matrices, the single risk assessment system during the technical system operation is obtained.

5 Conclusions

Based on graph theory, a conceptual model for managing a technical system has been developed, which serves as the basis for forecasting its operation.

The matrix of failure of the technical system elements is constructed on the basis of the ranking system for evaluating the parameters and determining the severity of the failure effects for the technical system elements; a risk management system for the failure of the technical system elements was developed based on the method of Failure Modes, Effects and Criticality Analysis. It is established that the result of forecasting is the probability of the technical system element malfunction within a given period of time. The construction of the conceptual model for managing a technical system based on FMECA, taking into account the failure risks, will allow identifying failures that, when they appear one at a time and in combination, have unacceptable or significant effects, and determine the failure risks that can have serious effects for the expected or required function of the technical system. The use of FMECA also eliminates costly modifications due to early identification of deficiencies in the technical system modules. The determination of the technical system bifurcation points will make it possible to determine the time points for the occurrence of the failure risks of the technical system elements and to make a decision about stopping the system and conducting maintenance and repair of the technical system elements depending on the severity of the failure effects.

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