On the Question of Reducing Technogenic Risks of Accidents in the Technical Systems of Buildings and Structures

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Abstract. The necessity of making changes to the functionality of a structured system for monitoring and managing engineering systems of buildings and structures is justified. An approach to modernizing the algorithmic support of a structured system for monitoring and managing engineering systems of buildings and structures is proposed in order to identify failures that lead to emergency situations at an early stage of their occurrence. The main features of the structure and application of technical systems of objects of various purposes, essential for the analysis of their technical condition, are determined. The necessity of developing and implementing a system for managing the technical condition of the studied systems is justified. A model for monitoring the operability of engineering systems of buildings and structures has been developed. The use of parametric statistics methods as a basis for the development of performance monitoring algorithms is justified. Regression equations are constructed as algebraic polynomials of various degrees, which are also the simplest combinations of elementary functions. Regression dependences of the monitored parameters of the diagnosed engineering systems on input influences are determined. Lists of these parameters are defined. The dependence of the reliability of determining the technical condition of engineering systems on the value of the confidence interval of the measured parameters was determined by numerical experiment. An algorithm for determining regression dependencies and a block diagram of the proposed algorithmic support are presented.

1. Introduction
A structured system for monitoring and managing engineering systems of buildings and structures (hereinafter referred to as SMIS) is a system built on the basis of software and hardware intended for the implementation of automatic monitoring of engineering and technical support systems, the state of the foundation, building structures of buildings and structures on the corresponding categories of objects, technological processes, engineering protection facilities and real-time transmission of information about the threat and occurrence of emergencies, including those caused by terrorist acts, via communication channels to the day-to-day management bodies of the unified state system for the prevention and elimination of emergency situations.
The main task of the SMIS is to promptly inform the operating organization and the executive authorities of the constituent entity of the Federation (MES) about emergencies at the facility associated with accidents in the engineering systems of the building, as well as with the violation of the integrity of the supporting structures of this building.

As for the technical condition of load-bearing structures, in the last decade their monitoring has reached a significant quality, but monitoring the state of engineering systems in many cases comes down to only fixing the failure of a particular system, characterized by a complete loss of its performance.

As the practice of operating buildings and structures for various purposes shows, accidents on technical systems lead to degradation effects on building structures. Unfortunately, very often it happens that failures in technical systems do not lead to a complete loss of their operability, but remain unnoticed, for example, the presence of leaks in pipeline systems laid hidden. And the long-term impact on the environment, as it seems, of an insignificant amount of coolant and water, can cause destruction of the structures in which these pipelines are located.

Therefore, solving the problems of determining the technical state of systems in order to identify precisely gradual failures is relevant.

2. Statement and solution of the problem

The development of a performance monitoring model is based on a priori information about the regularities of the functioning of the IS in a operational state. In this case, the mathematical description of the IS, as a system as a whole, characterized by input and output variables of different physical nature, must be performed on the basis of methods that allow the use of numerical realizations of these variables to determine the dependencies between them. These methods include parametric and nonparametric statistics methods.

In the presence of a representative training sample on the functioning of an object in a working state, it is advisable to use the methods of parametric statistics [1, 2], as they are much simpler in methodological and computational terms. In this case, to determine the values of the monitored parameters (CP) in the operational state of the object, it is necessary to establish the dependencies of the change in the output variables \( y_j \) (coordinates of the normalized observed states) on the input actions \( u_i \), which are also normalized. In general terms, these dependencies can be represented as:

\[
y_j = \hat{f}(U_{<j>}), \quad j = 1, n
\]  

(1)

The most common and proven method of parametric statistics is regression analysis [3]. However, the use of this method for setting dependencies (1) in an explicit form is legitimate only if the distribution of KP values in the operable state of the object corresponds to the normal law [2]. As is known, the distribution law of the sum of independent random variables with an unlimited increase in the number of terms approaches the normal one if the random variables included in the sum have variances of the same order and finite mathematical expectations. This means that the specific weight of each term tends to zero with an increase in the number of terms [4]. At the same time, in a working state, the IS is influenced by many different independent factors, among which there are no clearly prevailing over the rest. This can serve as a basis for accepting the hypothesis about the normal distribution of KP values, the condition for the validity of which is the adequacy of the synthesized dependences. For each CP, multivariate regression dependences of the form:

\[
y_{0j} = b_0 + \sum_{r=1}^{l_1} b_r u_r + F(u_1, u_2, ..., u_r) + \varepsilon, \quad j = 1, n
\]  

(2)

where \( y_{0j} \) – is the normalized (calculated) value of the coordinate of the vector of controlled variables; \( u_r, \ r = 1, l_1 \) – are the determining factors of the regression equation (input variables of the object); \( F(u_1, u_2, ..., u_r) \) – is the nonlinear part of the equation; \( b_r = (0, l_1) \) – regression coefficients; \( \varepsilon \) – is the residual random component.

From [2], the regression equations are constructed either as a combination of various elementary functions (power, exponential, trigonometric, logarithmic), or in the form of algebraic polynomials of
various degrees (which are also the simplest combinations of elementary functions – powers of the argument).

Equations in the form of algebraic polynomials have an advantage over equations in the form of combinations of elementary functions for the following reasons.

1. Any function that is continuous and bounded on a closed interval can be approximated with an unlimited degree of accuracy by an algebraic polynomial of the kth degree (Weierstrass approximation theorem [5–10]). The more complex the function, the higher the degree of the polynomial \( k \) is required.

With regard to the problems of monitoring the operability of the IS, the dependences of the controlled features on the input variables are considered as such functions. The explicit form of these functions is unknown due to the complexities of describing processes in IS. That is why they are approximated by regression equations. These functions can be considered as continuous due to the inertia of the processes in the IS, and as a consequence, the absence of various jumps of controlled features when changing the mode of operation of the IS. In addition, the functions are limited, since any controlled attribute of the IS can vary within a limited range.

Thus, all the mathematical conditions are fulfilled to provide an adequate description of the processes of functioning of the IS in a working state by regression equations in the form of algebraic polynomials.

2. Verification of the adequacy of the regression equation to experimental data using Fisher's criterion (as the most complete and comprehensive verification) is possible only if it has the form of an algebraic polynomial. This is explained by the possibility of calculating the number of degrees of freedom at which the estimate of the residual variance is determined, only for an equation in the form of an algebraic polynomial. Based on the above, the construction of multivariate regression dependencies (2) in the case, for example, of an algebraic polynomial of the second degree, has the form:

\[
F(u_1, u_2, \ldots, u_r) = b_{12}u_1u_2 + b_{13}u_1u_3 + \ldots + b_{1l}u_1u_l + b_{1l+1}u_1^2 + b_{22}u_2^2 + b_{l1}u_1^2
\]  

(3)

Within the framework of this work, all regression dependences are constructed in the form of algebraic polynomials of controlled features from the input parameters. Taking into account expression (2), the objective function of the regression analysis by the least squares method has the form:

\[
R = \min_{b_j \in \mathbb{R}} \left\{ \sum_{i=1}^{n} \left( y_{ij} - \left( b_0 + \sum_{r=1}^{l} b_{ir}u_{ir} + F(u_{11}, u_{12}, \ldots, u_{ir}) \right) \right)^2 \right\}.
\]  

(4)

From this equation, the average values of \( y_{0j} \) (estimates of the mathematical expectation) of the controlled features in the operational state of the object are determined. The specified values can be interpreted as the coordinates of a point that moves in \( n_1 \)-dimensional Euclidean space under the action of the input variables. Thus, the model takes into account any changes in the input actions.

Further, relative to the mean values, which are obtained from equations (2), the admissible intervals \([y_{0j}^{\text{bottom}}, y_{0j}^{\text{top}}]\) are allocated. Depending on the conditions of the intended use of the object, the indicated intervals may be different. Taken together, they form an area of an operable state in \( n_1 \)-dimensional Euclidean space. This area also moves under the action of the input variables, since all intervals are set relative to the coordinates of the moving point. Based on this, it is obvious that the proposed approach makes it possible to control the TS of an object in any operating modes during its use for its intended purpose.

An object is considered operational if it is established that all CPs comply with the permissible limits, i.e. condition is satisfied:

\[
\bigcap_{j=1}^{n_1} \left( y_j \in \left[ y_{0j}^{\text{bottom}}, y_{0j}^{\text{top}} \right] \right)
\]  

(5)
This condition uniquely defines a hyperplane in the \( n_1 \)-dimensional Euclidean space, which separates the regions of operable and inoperable states. Failure to meet condition (5) is considered as a quantitative setting of the refusal criterion.

To determine the permissible intervals of change of controlled signs:

\[
\Delta_j = \left[ y_{0_j}^{\text{bottom}}, y_{0_j}^{\text{top}} \right] \quad j = 1, n_1
\]

A technique has been developed based on the analysis of the training sample for the operable state of the IS and the properties of the normal distribution (\( y_{0_j}^{\text{bottom}} \) – is the maximum permissible lower value of the \( j \)-th monitored feature in a workable state, \( y_{0_j}^{\text{top}} \) – is the maximum permissible upper value of the \( j \)-th monitored feature in an operable state). This technique allows you to set any relationship between the confidence probability of the admissible values of the KP in the area of the operable state and the value of the interval \( \Delta_j \), as well as to determine its lower \( y_{0_j}^{\text{bottom}} \) and upper \( y_{0_j}^{\text{top}} \) the boundaries.

3. Theoretical foundations of the proposed method

Any interval specified with respect to each coordinate \( y_{0_j} \) corresponds to a certain confidence probability \( P_{\text{confidential}} \) of falling into this interval of values of the \( j \)-th monitored feature of a workable object. This probability is determined from the ratio:

\[
P_{\text{confidential}} = \int_{y_{0_j}^{\text{bottom}}}^{y_{0_j}^{\text{top}}} f(y_j)dy_j,
\]

where \( f(y_j) \) – is the distribution density of the values of the \( j \)-th controlled feature.

The boundaries of the permissible intervals are proposed to be set through the estimates of the standard deviations \( \sigma_j \) of the determined parameters of the corresponding regression equations:

\[
y_{0_j}^{\text{bottom}} = y_{0_j} - k\sigma_j,
\]

\[
y_{0_j}^{\text{top}} = y_{0_j} + k\sigma_j
\]

where \( y_{0_j} \) – is the estimate of the mathematical expectation of the controlled parameter, \( \sigma_j \) – is the standard deviation for the \( j \)-th controlled feature, \( k \) – is the coefficient that determines the value of the interval of permissible changes in the controlled features.

The model for monitoring the performance of technical systems of special objects consists of the following steps [11–20].

1. The values of estimates of mathematical expectations (MO) are determined for each controlled feature (2).

2. The values of the standard deviations (SKO) are determined for these controlled signs.

3. The required level of reliability is set for the correct determination of the technical state of the elements of the controlled system.

4. The theoretical value of the coefficient is calculated, which determines the size of the interval of permissible changes in the controlled features (8).

5. The fulfillment of condition (5) is checked. If it is fulfilled, the system is operational, and if it is not fulfilled, proceed to the search for the failed element.

Thus, the outlined approach to the construction of a mathematical model for monitoring the operability of an IS makes it possible to monitor its functional suitability without explicitly setting the aggregated state of an inoperative IS.
4. Conclusion

One of the most important features of the presented algorithmic support is that the development of software for monitoring the operability of the IS is accompanied by the need to overcome the factors of complexity of its construction and operation, as well as the uncertainty of information about the patterns of changes in the technical state. Therefore, it is necessary to apply methods that allow modeling in the presence of a limited amount of heterogeneous a priori information and, in general, adequately display the properties of the IS that are essential for analyzing the technical state.

The proposed methodological approach provides for the invariance of the software to the physical nature of the components of the input and output processes of the IS.

The use of this approach makes it possible to identify the occurrence of failures at the stage of their «inception», which entails the timely adoption of measures by the operating body to prevent accidents, and therefore reduces man-made risks during the operation of engineering systems of buildings and structures.

5. References

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