Risk acceptance criteria for complex technical systems

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Abstract. The article provides theoretical generalization and detailing of risk analysis applied to the structures of complex technical systems based on its fast-evolving theory. Using previous studies, the author suggests choosing a metallurgical overhead crane as a facility related to such systems. The following three different risk analysis patterns are feasible during safety assessment and technical diagnostics: based on the operation life, based on the state and based on the damage resulting from making wrong managerial engineering decisions. Risk acceptance criteria applied to the complex technical systems under study are set based on stress strain behavior parameters including actual stresses and deformations along with mechanical property characteristics of materials. A decision on further operation of the structure or on ceasing the operation thereof is made when comparing safe acceptable and actual values of stresses and deformations. A table is created for such decision-making. The function of risk related to the damage resulting from making wrong managerial decisions is presented. Further development of such approach will allow identifying methodological recommendations for making decisions on future operation of complex technical systems in a more substantiated way.

1. Introduction
Any complex technical system includes a great number of hazards within which certain negative impact on facilities or elements related thereto is likely. For this reason, the formation of potential risk areas and risk acceptance criteria represents a relative task for each of the specified hazards. Quite a lot of attention is given to risk analysis and assessment [1-21]. However, the specific nature of the decision related to the feasibility of operation based on the risk analysis applied to complex technical systems according to the operation life and the state involves setting the target risk acceptance \( R_f \) for the tolerance probability of failure, accident or disaster.

2. Materials and methods
The conceptual foundation of risk analysis applied to a complex technical system can be presented in figure 1.
The control of risk characteristics at the operation stage is practically not considered at the moment, regulated values of acceptable risk are not established and safety is ensured by means of expert evaluation using technical diagnostic methods [1,2]. Therefore, when a defect or damage is detected in structural elements of complex technical systems, it is logical to find the answer to the following question: how hazardous are they?

The decision-making pattern depends on the following two methods of operation [1]: technical operation based on the operation life and technical operation based on the state. According to the first method, the complex technical system is operated until the expiry of the standard life. The second method allows operation until the breakdown occurs or the condition is reached where there is a high probability of breakdown (accident, disaster).

3. Results

We define the problem of risk analysis applied to a metallurgical overhead crane structure representing a complex technical system during the operation stage and attempt to resolve this problem [9,10].

Let’s assume that the state of the structure with measurable parameters is assessed $Q(t)$. Based on this assessment and using the criteria we must determine the state $s_i$ of the technical system with an array of possible states $S$:

$$s_i(Q,t_k) \in S.$$  \hspace{1cm} (1)

Then we forecast the dynamics of the facility state over a particular given time interval $\Delta t$:

$$s_i(Q,t_k) \rightarrow s_j(Q,t_k + \Delta t).$$  \hspace{1cm} (2)

In this case, the interval $\Delta t$ must be linked to the design operation life. When $t_k + \Delta t$ goes beyond the standard operation life, the transition to this state is not accepted and the technical system is withdrawn from operation. Otherwise, the facility is operated with further assessment of its state.

When operation is based on the state, the following will be considered acceptable. The system state must not refer to the array of failed states (accidents, disasters) $S_f$:

![Figure 1. Flowchart of the technical system risk analysis.](image-url)
The probability $P$ of falling on an array of failed states (accidents, disasters) at the time $t_k + \Delta t$ will not exceed the given value:

$$P\{s_i(Q,t_k + \Delta t) \in S_f\} \leq [R_f].$$

$R_f$ refers to the acceptable risk limit.

An array of assessed parameters $Q$ includes the characteristics of stress-strain behavior of structural elements, defects, mechanical property characteristics and crack resistance of materials. We will take the characteristics of actual stresses and deformations and the characteristics of mechanical metal parameters as main parameters.

Acceptable risk requirements are established during the first stage. As a result, safe or acceptable and actual stresses and deformations, and the characteristics of mechanical metal parameters are determined.

Then, the risk acceptance criteria are established. Critical stress and corresponding deformation serve as the acceptance criteria of permissible state. When the actual values happen to be lower than the acceptable limits, the current state is defined as being safe and the state over time interval $\Delta t$ is forecast.

The acceptance criteria for the forecast state include critical deformation and stresses assessed with due regard to the entire array of actual mechanical property characteristics, external environment impact parameters and stress-strain behavior. When the forecast value of stresses and deformations happens to be lower than critical values, the system is operated within the given interval. In other cases operation is terminated.

Despite the accurate calculations of stresses and deformations, their path function remains random and unknown within the operation interval. In this case, the state of the structure is defined by the density of operation life distribution or the density of stress and deformation distribution. When the density of the operation life is known, we determine the probabilistic assessment of the residual operation life and when the density of stresses and deformations is known, we assess the probability of the structure’s transition into the limit breakdown state (failures, accidents, disasters). By taking into account damages and losses associated with making wrong managerial decisions, we perform risk analysis related to the damage resulting from mistakes.

Thus, when operating potentially hazardous complex technical systems the following three risk analysis patterns are feasible: based on the operation life, based on the state and based on the adopted managerial decisions.

Assuming that the state of the structure can be referred to the accident-free array $S_0$ - hypothesis 1 or to the pre-accident array $S_f$ - hypothesis 2, we will create a table of decisions made with regard to referring to a particular array based on the comparison between actual and safe acceptable stress and deformation values – Table 1.

**Table 1. Decisions on acceptable risks.**

| System state | $S_0$ | $S_f$ |
|--------------|-------|-------|
| Decision     | 1     | 0     |
|              | 1     | 1     |
|              | 0     | 1     |
|              | 1     | 1     |

1 – referring to this array; 0 – not referring to this array.

This table is filled out based on diagnostic study results and actual data.
We will present the probability of wrong managerial decisions as the probability that the structure is actually in a safe state and the values of stresses or deformations refer to unacceptable ones:

\[ P_1 = P(S_0) \int_{\sigma} f\left(\sigma, t_i \middle| S_0\right) d\sigma. \]  

(5)

\( \sigma \) refers to unacceptable values of stresses (deformations).

The probability of wrong managerial decisions represents the probability that the structure is actually in pre-accident state and, based on the diagnostic data, it is found that the values of stresses and deformations are less than the acceptable limits:

\[ P_2 = P(S_f) \int_{\sigma} f\left(\sigma, t_i \middle| S_f\right) d\sigma. \]  

(6)

When entering economic losses \( U_1 \) - termination of operation and facility maintenance and \( U_2 \) - damage caused by the breakdown (failure, accident, disaster) resulting from a wrong decision, the risk function will be as follows:

\[ R(t_i) = U_1 P(S_0) \int_{\sigma} f\left(\sigma, t_i \middle| S_0\right) d\sigma + U_2 P(S_f) \int_{\sigma} f\left(\sigma, t_i \middle| S_f\right) d\sigma. \]  

(7)

Deformation and stress value densities can be described by using known methods. To assess probabilities of hypotheses \( P(S) \), new special methods of probability theory or, for example, nonlinear dynamics need to be applied [13], in terms of frames and wild cards.

4. Conclusion

At the moment, the acceptable standards of allowed risk and the tolerance probabilities of failures are developed only for nuclear reactor designs [1,2]. This article adds to the known risk analysis methods for structures of potentially hazardous facilities used at iron and steel plants – in particular, metallurgical cranes, which represents an element of academic novelty. The acceptable risk level for one year of operation can be considered as \( 10^{-5} \ldots 10^{-6} \) for such hazardous structures.

The presented approach generalizes and details the already known methods of risk analysis and represents practical interest from the perspective of developing methodological recommendations for solving model and practical problems of risk analysis.

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