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MATHEMATICAL EVALUATION OF MECHANICAL CONSTRUCTION SAFE LOADING

YURY ANATOLYEVICH IZVEKOV, ELENA VLADIMIROVNA KOBELKOVA, NADEZHDA ANDREEVNA LOSEVA, VLADISLAV VLADIMIROVICH DUBROVSKY AND EVGENIA YUREVNA HAMUTSKIKH

Nosov Magnitogorsk State Technical University, Lenin ave., 38, Magnitogorsk, 455000, Russian Federation

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ABSTRACT

The article analyzes an interdisciplinary approach of nonlinear dynamics and a body of mathematics of applied catastrophe theory for mechanical system safety management – a load-bearing element of the metallurgical crane bridge. An actual mechanical system with three rank parameters and two commandersis simulated, with the use of specified mathematical apparatus of an applied catastrophe theory. The values of the coefficients are obtained, in which the state of the load-bearing element of the metallurgical crane bridge may be in dangerousand catastrophic conditions, which gives ample opportunities in solving the problems of technogenic safety and risk theory. The proposed approach couldprovide the technogenic safety not only of metallurgical traveling cranes, but also of various other real-world structures: bridges, arches, hoisting machinery.

INTRODUCTIN

A generalized condition of the analysis and mechanical system safety management can be represented in the form (Frolov *et al.*, 2006; Izvekov *et al.*, 2014; Izvekov *et al.*, 2014):

$$R(t) = \sum_i P_i(t) \cdot U_i(t) \leq [R(t)] = \frac{K_\varepsilon(t)}{n_\Sigma} = m_\Sigma Z(t) \qquad (1)$$

In its implementation, one must consider the following:

– The risk R(t) is a combination of probabilities P(t) of accident, catastrophe, damages conditions U(t):

$$R(t) = \sum_i P_i(t) \cdot U_i(t); \qquad (2)$$

- Risk criterion safety can be written as

$$R(t) \leq [R(t)] = \frac{R_\varepsilon(t)}{n_\Sigma}; \qquad (3)$$

***Corresponding author's email:** yuryizvekov4@gmail.com

Where n_R – reserve for risks ($n_R \geq 1$); $R_c(t)$ – critical risk;

- it is necessary to include measures with the costs $Z(t)$, associated with the emerging risks $R(t)$ in order to achieve a given safety level and safety management:

$$Z(t) = \frac{R(t)}{m_z}; \qquad (4)$$

mZ - cost-effectiveness ratio ($mZ \geq 1$).

The main element here is an analysis of the key parameter $P(t)$. Let us analyze a multidisciplinary approach to determine this parameter for the load-bearing element of the metallurgical crane bridge.

METHOD

Numerical mathematical modeling and assessment of the safe load of supporting construction, the main beam of the metallurgical traveling crane, is implemented in terms of anapplied catastrophe theory.

RESULTS

The combination of the probabilities of accidents and catastrophes not only of mechanical systems in smelting industriescould be identified and predicted if there is enough extensional statistical material, or at least there are known details of such incidents. As a rule, the owner investigates such incidents privately andpromptly if they have not had much publicity. Therefore, accidents and catastrophes occur where we do not expect for them. This implies that modern methods of the description and determining of these events are inadequate (Frolov *et al.*, 2006; The Royal Society, 1993; Boulding, 1956; Brushlinsky *et al.*, 2003; Izvekov *et al.*, 2014; Izvekov *et al.*, 2014; Kumamoto *et al.*, 1996; Hammad *et al.*, 2014; Taguchi, 1985; Sorensen, 1973). Moreover, there are cases when the crane is broken, having worked out for three years, but at the same time, there are cranes, which operate satisfactorily in its eighth decade.

Likely, it is better to restrict oneself with short-term forecasts or to look for appropriate ways to compare the model response and prototype system. Thus, I. Prigogine and I. Stengers suggest that an important and measurable characteristic is an invariant measure of the dynamical system (Prigogine, Stengers, 1994). Herein interesting is the use of a relatively new interdisciplinary approach – a nonlinear dynamics. However, most data analysis algorithms, using nonlinear dynamics, are effective when the dimension of the phase space of the system is low. For diagnostic variable of the probabilities combination $P(t)$ of accidents and catastrophes we can define a measure in the phase space associated with the dynamical system. This measure allows multitude to put a number in the phase space, which can be interpreted as a probability that the trajectory will resort tothe studied multiplicity. In this case, it does not change, i.e. invariant (Malinetskii, Potapov, 2000; Tabor, 2001). In addition to the nonlinear dynamics within the multidisciplinary approach,a study and analysis of the problem from the perspective of the applied catastrophe theory is of a special interest (Arnold, 1974; Arnold, 1992; Gilmore, 1993; Sadovnichii *et al.*, 2001; Poston *et al.*, 1998; Sanns, 2000; Saunders, 1980; Thompson *et al.*, 1982). The latter is quite well elaboratedon the models, but its interpretations on real-world constructions are only far and few between. Furthermore, there are no methodological instructions for various procedures at all.

As a mechanical systemwe will investigate the load-bearing structure of the metallurgical traveling crane beam. The selection of the mechanical system has already been described (Izvekov *et al.*, 2014). This mechanical system is described as a Lagrangian dynamical system with holonomic constraints (Arnold, 1974).

Let us characterize the real-world construction model: we shall introduce the coordinates of the system status x_1, x_2 x_3, which also will be calledthe rank parameters and control parameters that will represent the external load on the system and defects that may occur in the manufacture of construction units, in the course of operation, respectively, c_1, c_2.

The total energy E of the system is the sum of the kinetic K and W potential energies:

$$E = K + W \qquad (5)$$

The kinetic energy is determined by the quadratic form in generalized velocities x_i, and the potential – by the function of the state variables and control parameters $c \, \varepsilon R_2$.

Since the load-bearing structure of the crane appears as a curving beam, it is convenient to represent the function describing the behavior of the beam in the form of a Fourier series:

$$y(x) = \sum_{j=1}^{\infty} a_j \sin \frac{j\pi x}{l}; \qquad (6)$$

$y(x)$ – the deviation of the beam as a function of the distance x from one end;

l – a coordinate of the other end of the bar;

a_i - Fourier coefficients that define the shape of the beam and play the role as state variables in the control parameter – transversal load Q.

Based on our practical purposes and reflections of (Arnold, 1992; Gilmore, 1993), a beam state is a dangerous if the amplitude of its initial bending exceeds the safe values: specified in the manual. Let us consider a maximum load capacity of a vibrating beam under the dynamic loading. The vibrations occur near the state of static equilibrium. Since the amplitude of the bending is zero gradient, then maximum safe load Qswill be determinedby a safe bend. Based on the suggestions of (Gilmore, 1993), the maximum load-bearing capacity can be defined as Q, and wherein the amplitude of bending reaches the states. For systems without defects a change in kinetic energy is:

$$\Delta K = \frac{1}{4}\left(\frac{\pi}{l}\right)^2 (Q_1 - Q_s) s^2 + \frac{3Q_s l}{64}\left(\frac{\pi}{l}\right)^4 s^4. \quad (7)$$

$$Q_s = \frac{Q_1 - \left(\frac{\Delta K}{l}\right)\left(\frac{2l}{\pi s}\right)^2}{1 - 3\left(\frac{\pi s}{4l}\right)^2}. \quad (8)$$

For such systems, which breakdown occurs in accordance with the type of catastrophes A_{+3}, asafe load sensitivity both to defects and dynamic loads will be quite consistent.

Let us examine the model of the load-bearing structure in the range of operating loads on the crane from Q1 = 165 MPa (megapascal) with a beam span length l = 25 m (meter). The results of the study are presented in the Figure 1.

The red line in the Figure shows the allowable stress for the constructional material of metallurgical traveling crane $Q_{tolerance}$ = 270 MPa. It can be seen that for values of $a_1 < 11$ the beam will be loaded safely, and for $a_1 > 11$ the beam will be at risk, catastrophic condition, leading to a possible reduction of a load-bearing capacity of the structure and its destruction. The reason for reduction of the carrying capacity is a dynamic bending load. In addition, the average kinetic energy introduced by bendingis regarded as a dynamic parameter of imperfection. This means that the mechanical construction is relatively stable at zero or small vibrations until the kinetic energy becomes so large that it may overleap the potential barrier to another, more equilibrium structure. Various constructions may be identical to each other in their potential functions but different in the kinetic ones. Therefore, their reaction to the static load will be the same, but different under dynamic loads.

DISCUSSION

Knowing the values of dangerous and catastrophic state of load-bearing structure of the metallurgical traveling crane, we can determine the probability of an accident of this system and manage the technogenic safety of the part of manufacturing process or the production in the aggregate. The data obtained converge satisfactorily to real, since $Q_{tolerance}$ = 270 MPa. It is necessary to develop guidelines for technogenic safety management of such systems, based on the proposed approach, placing them in the regulations for a number of identical mechanical systems. A prerequisite here should be the equality not only of potential components, but also kinetic. And of course, we must remember that the analysis of the dangerous condition comes down not only to the algorithms of elementary catastrophe theory, but also requires a variety of subjectsof the interdisciplinary approach, an acumen, aspirit of the engineer, a human being.

CONCLUSION

Thus, only after having numericallydetermined the values of safe and dangerous conditions, its corresponding loads, sensitivity of the breaking load of a carrying structure of the metallurgical traveling crane, havingset their permissible values, we could be able to judge upon the determining parameter of the probability combination of the accidents and catastrophes occurrence and damages from them; in order to reduce emerging risks in such systems, and in satisfactory concourse of circumstances to reduce the cost of the associated package of measures.

It is necessary to point out that the article does not consider the weight of the beam (it plays an important role) and some other defects. It is necessary to consider the potential and kinetic components of the construction for different types of catastrophes, the effects of different classes'disturbances, balance, stability and buckling.

A continuation of consideration of interdisciplinary approach subjects of nonlinear dynamics, applied catastrophe theory, probability theory and others forvarious constructions technogenic safety management assumed as highly important and challenging.

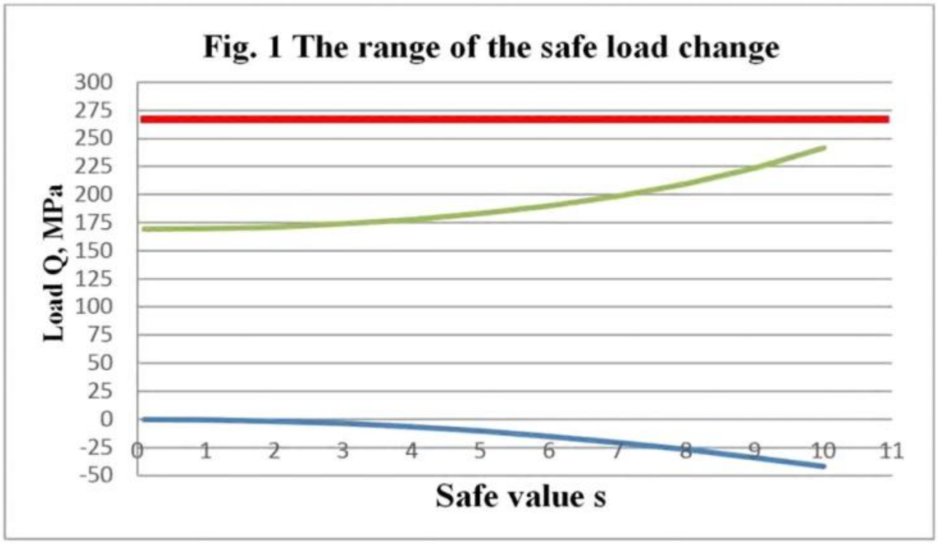

Fig. 1 The range of the safe load change

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