

Survivability of the locomotive cabin at interval estimation of obstacle parameters

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Abstract. The article considers the multiparameter problem of the mechanical system behavior and its survivability when destructing individual elements. The technique for constructing the area of safe operation of the cabin of the GT1-h gas turbine locomotive was illustrated on the example of collision of a locomotive with an obstacle at a crossing. The main parameters determining the energy of interaction between the cabin and the obstacle was singled out, and their influence on the survivability of the structure was analyzed. The finite element method was used to calculate the load-bearing capacity of a power frame with a buffer device in the initial state and after the destruction of individual structural elements by the dynamic strength criterion. The force of elastic interaction between the locomotive and the obstacle was estimated through the spring, the rigidity of which was estimated on the basis of the finite element calculation results. As a result of the calculations, proposals were developed to strengthen the cabin frame to ensure the safety of the crew and the instrument part in case of unauthorized collision with an obstacle of considerable mass and violation of the speed regime.

Introduction

The problem of maintaining the load-bearing capacity of a metal structure after destruction of individual elements is known as the problem of the survivability of structures. Estimation of a real structure survivability is reduced to solving a nontrivial multiparameter problem of constructing a safe operation area in a certain functional space [1-5]. The task of such a large scale can have an ambiguous solution, different levels of strictness in formulation of particular problems, and ways of presenting the results. The situation is complicated by the fact that the initial data on the design and the nature of external impact are almost never sufficiently complete. For this reason, there is no single scheme or any single-valued algorithm for solving such problems. In connection with this, the search for approaches to a more accurate estimation of the survivability of real mechanical systems under operating conditions and, in particular, under excessive loads is relevant. An example

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is the problem of survivability of a locomotive cabin in a collision with an obstacle on a crossing, which is considered in this article.

Methods for estimation of protection of the cabin's power frame from destruction in collisions with obstacles are reduced to calculating the efficiency of buffer devices [6-8]. With that, the obstacle appears as an absolutely rigid body, which causes incorrect estimation of the interaction effort. To clarify the effort, the locomotive and obstacle are treated as two point masses interacting through a spring of equivalent rigidity, which is determined taking into consideration of compliances of the cabin with the buffer device and the obstacle. Since the type of obstacle is not known in advance, interval estimation of its structure rigidity is given. The studied area of safe combinations of obstacle parameters is determined by the equality of the determined interaction force in a collision and the load of the limiting state of the cabin power frame determined with the finite element calculation.

It is believed that the most reliable information about the consequences of such external influences and possible scenarios of destruction is provided by performing field tests and crash tests [9-12]. But such information is possible for relatively inexpensive objects. It is often statistically unreliable and is not comprehensive, since it is rarely possible to provide space-time synchronization of loads due to the random nature of the external impact. For these reasons, the task of calculating the quantitative estimation of the extreme loads spectrum of the structure that limits the area of safe operation is actual at the design stage. The purpose of this work is to develop and implement an algorithm for quasistatic calculation of the limiting state of the cabin structure, in which the kinetic energy of the impact, the compliance of the cabin structure and obstacles is taken into consideration in addition to the masses and the velocity of the composition.

Study methods

GT1-h gas turbine locomotive with a buffer device of passive protection was selected as a specific object for the proposed demonstration of the approach [1, 10]. The power frame of the gas turbine locomotive cabin is a three-dimensional beam-rod structure made up of more than a hundred bent profiles and open-ended beams (Fig. 1). The buffer device consists of a frontal beam, fastening braces and six honeycomb elements between the frontal beam and the header. Experimental study of such systems with a review of the loading conditions is not possible. Costly field tests are very informative, but they cannot give a statistically reliable result. The most affordable way to calculate the carrying capacity of a complex design is mathematical simulation and computational experiments to determine the stress state.

The ANSYS-14 calculation package, the Uranus supercomputer of the Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences and the quasistatic approach to solving dynamic problems was used in this work. Such approach is typical, for example, for the catastrophe theory [13], where dynamic phenomena in a mechanical system are predicted on the basis of equilibrium surfaces analysis. The carrying capacity of the cabin was determined in calculation of the stress state under various loading conditions. As the elements of the cabin are basically thin-walled structures, the SHELL-181 finite element [14-19] is used in the shape model that consists of over 450 thousand finite elements.

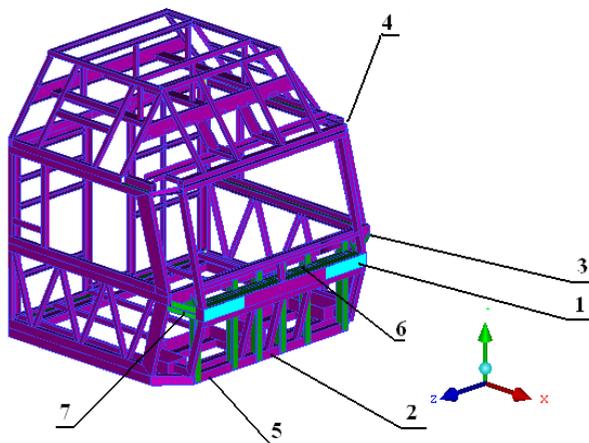


Fig. 1. The design layout of the GT1h gas turbine locomotive cabin drawn in the ANSYS ICEM CFD 14.0 application, where 1 is the frontal beam, 2 is fastening elements, 3 is the power belt, 4 is the upper harness of the cabin, 5 is the lower frame of the cabin, 6 is the set of honeycomb elements, 7 is side stops.

The dynamic nature of impact interaction between the cabin and the obstacle at a crossing is taken into consideration in the material model. It was assumed that the material of the cabin elements (3sp5 steel with the tensile strength of $\sigma_V = 500$ MPa) remains elastic until the failure at the dynamic yield point of $\sigma_{DY} = 1,3\sigma_V = 650$ MPa [20]. The strength criterion of a single structural element is adopted in the form of

$$\sigma_V \geq \sigma_{DY} \tag{1}$$

where σ_V is Mises' equivalent strain.

Calculation of the stress state of the cabin with destruction of individual elements by criterion (1) showed that the limiting state of the entire structure is only reached when the buffer device is completely destroyed. The corresponding limiting load on the frontal beam for a given value of contact area S_f integrally determines the resistance to damage to the entire cabin structure

$$P_{prel} = \iint_{S_f} q dx dy \tag{2}$$

where q is the contact load at the moment of impact.

On the other hand, the maximum force of interaction between the locomotive and the obstacle as two point masses can be estimated by the formula [1, 10]

$$F_{max} = v\sqrt{cm_2} + F_r \tag{3}$$

Here, c is the equivalent rigidity of the system, which is determined from following expression by analogy with the successive connection of two springs

$$c^{-1} = c_c^{-1} + c_{ob}^{-1} \tag{4}$$

where c_c is the rigidity of the cabin with a buffer devices determined at the calculation of P_{prel} by the results of the finite element analysis. The mass m_1 of the train with the gas turbine locomotive reaches four thousand tons and more. Formula (3) output assumed $m_1 \gg m_2$.

Obstacle rigidity c_{ob} can be determined in a similar calculation in the specific case. As the parameters of a potential obstacle are not known before the collision, c_{ob} can only be estimated by the interval value of ratio $r = c_{ob}/c_c$, $r \in [0,1;1]$. By changing this ratio, it is possible to predict possible interaction force F_{max} with obstacles of different design. This includes the conditions regulated by European standard EN 15227:2008 [11].

Equality of formula (2) and (3) allows revealing the area of safe combinations of obstacle parameters, in which the power frame of the cabin does not collapse. Therefore, the safety of machinists and the instrumental part will be ensured. The results of calculations are presented in the form of a limiting surface in the three-dimensional space, the mapping of which on the obstacle parameters plane gives the required area of safe operation of the cabin.

Results

The calculated dependences of force P on displacement w of the cross section at the center of the frontal beam for various states of the system are represented by straight lines 1, 2 and 3 in Figure 2.

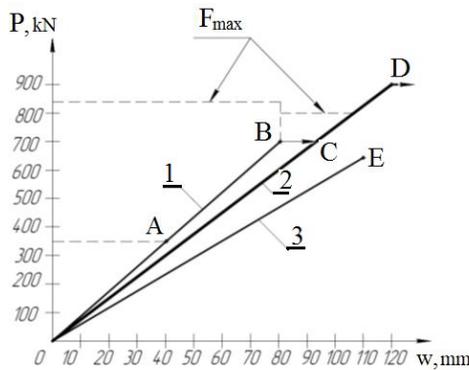


Fig. 2. To limit load calculation algorithm P_{prel} .

The calculated straight lines are built for various states of the system. Straight line 1 in Figure 2 was built for the initial state; the destruction of the anchoring struts (point A) did not affect the system rigidity. Straight line 2 was built for a cabin without honeycomb elements that collapsed under load P_b (straight line 1). Straight line 3 was built for a power frame without honeycomb elements that collapsed under load P_d (straight line 2). Destruction of honeycomb elements causes transition of the BC to new load line 2. At the same time, no destruction of the power frame occurs. The transition dynamics must be

neglected in view of the overall impact stress nature. Transition from point D is impossible, as the destruction of the frontal beam will cause destruction of the cabin power frame. Therefore, the carrying capacity of the cabin will be determined by the value of the ultimate integral load $P_{prel} = P_D = 920 \text{ kN}$.

It should be noted that the destruction of the system elements causes a reduction in cabin rigidity c_c and, in accordance with expression (4), to the reduction of the equivalent rigidity of the “cabin-obstacle” system. Then, according to expression (3), the value of the maximum interaction force F_{max} is also reduced. In the example considered, this reduction is small (see the dashed line in Figure 2) and can be neglected. In the general case, using the equality of expressions (2) and (3) to construct the desired boundary G_q , the calculated stiffness c_c shall be determined by the slope of the line on which value P_{prel} is determined.

Let us not down the equality of expression (2) and (3) that connects the parameters of the cabin and obstacles in the form of an implicit function

$$v\sqrt{c(f)m_2} + F_T(m_2) - P_{prel}(\sigma_{DY}, f) = 0 \tag{5}$$

Such function defines a certain hypersurface in the multidimensional space of the parameters studied. Visual representation of such surface can be obtained for three or four variables. For the example considered, coefficient of the the frontal beam area overlapping $f=1$. Surface (5) is presented in Figure 3 (a) at the set intervals of $m_2 \in [1000;20000]$ kg and $r \in [0;1]$.

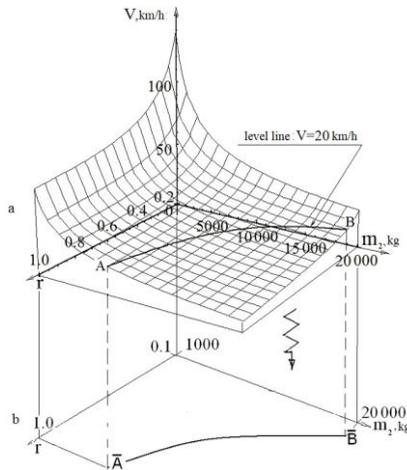


Fig. 3. Design hypersurface: *a* is the cabin destruction surface; *b* is the projection of the level line onto the obstacle parameters plane.

According to the rules for the operation of the rolling stock of railways [6], the recommended speed of the train at a crossing must not exceed 20 km/hour. Level line AB is assigned on the surface corresponding to the given speed value, and Figure 3 (b) shows its projection \overline{AB} onto the obstacle parameters plane. Line \overline{AB} is the studied boundary G_q of the area of safe operation of the cabin at a crossing within the specified ranges of the mass change and the obstacle structure rigidity. The structure will be survivable until the obstacle parameters are located within the area bounded by G_q . Destruction of the cabin

with the combination of obstacle parameters within this area is only possible because of exceeding of the recommended speed at a crossing.

Conclusion

The performed calculations of the gas turbine locomotive cabin allowed making a reasoned conclusion about the need to strengthen the structural frame of the structure. The calculation algorithm and the developed finite element model of the cabin with a buffer device can be adapted to structural changes without large expenditures. The procedure for calculating the boundary between the structure and the sacrificial elements will not change with another set of investigated parameters, including standard variants. A significant complication in calculations of the load is possible if the material model becomes more complex. In general, a relatively simple quasistatic approach allowed solving the task set and finding the area of safe combinations of the main obstacle parameters for the cabin. Unlike standard approaches, the presented calculation takes into consideration the rigidity of the cabin and obstacles.

The guaranteed area of safe operation of the structure is clearly indicated by the assumptions, limitations and criteria of the limiting states of a particular methodology for a typical calculation for regulated combinations of loads. When an over-normative load is applied, the definition of the area of safe operation of a specific object that provides protection for personnel and equipment is associated with solution of a number of new non-trivial tasks. First of all, this is due to incompleteness of studies of the phenomenon of destruction of materials and structures, as well as due to the fact that the parameters of external influence in a non-emergency situation have not been fully determined in advance. In the absence of rigorous solutions to statistical dynamics in computational practice, deterministic engineering estimates of the limiting state of the entire complex structure will be in demand.

Further studies of this problem are related to refinement of dynamic properties of the structure material under impact loading. They are also related to refinement of the input parameters of the problem in accordance with possible scenarios of collision of the locomotive with various obstacles. Consideration of physical and geometric nonlinearity of the problem can provide a certain refinement of survivability prediction.

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