Construction and testing of a parametric criterion of mechanical damage of an employee or an athlete based on the model "impact - weakening - carrying capacity"

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Abstract. The issues of concretization and expansion of the parametric model “impact - weakening - carrying capacity” application for describing injuries to workers in both mechanical engineering and sports are considered. Based on previously obtained results from other studies, injuries were selected and described by severity (mild, moderate, severe). For quantitative assessment of injuries that often occur both in production and in sports, the article developed and tested a parametric criterion for mechanical damage of an employee or an athlete based on the model “fuzzy impact - fuzzy bearing capacity”. The results obtained can be useful for a comparative analysis of working and sports conditions and substantiation of methods and means of protection against the negative action of mechanical factors.

1. Formulation of the problem
According to the general algorithm [1], a measure of the certainty of mechanical damage to a person can be found by classifying possible outcomes, establishing and (or) choosing their parametric models based on the classical model “impact (load) - weakening - susceptibility (strength)” and calculating the probability or possibility of outcomes implementation according to expected values and intervals of their spread [1,2].

In this formulation, the development of a parametric criterion for mechanical damage to an employee or athlete based on the “impact - weakening - carrying capacity” model is the main issue for a unified quantitative description of injuries in both machine-building and sports spheres.

2. Introduction and description of the main outcomes of mechanical damage
Let us introduce and consider the following unfavorable outcomes (UO) that can occur in the work or competition area, where y (x) = 1 is a logical condition for the occurrence of an accident or outcome, examples of which for athletes - volleyball players were systematized in the dissertation of Mamatchenko N.S. [4] and are presented in table 1:

| x1  | UO 1 | injury with loss of ability to work (crack / fracture of one finger when the worker’s hand is in the stamp space during the operation of the press); |
| x2  | UO 2 | injury with long-term disability (fractures of two or more fingers / hand when the worker’s hands are in the stamp space during the press operation); |
| x3  | UO 3 | lethal outcome (fracture of the bones of the skull base when the worker’s head is in the stamp space during the work of the press). |

By definition, taking these outcomes into account, the general logical model of an incident of the type under consideration is:
3. Introduction and description of the factorial parametric model of the incident

Most often, a safety examination is carried out in the absence of accurate and (or) complete information about the prerequisites for incidents in the technical system.

Since the “impact parameter” is a characteristic of the “environment”, the expert uses calculation and analytical methods to find it. Whereas the “susceptibility parameter” is a characteristic of the ability of an object (or subject), expressed in terms and values of the impact parameters, to occur in the system of an incident (an unfavorable outcome). Moreover, the parameters of susceptibility are established, as a rule, experimentally.

Table 1. Time of disability for volleyball players of different roles.

| Variety of roles | 1  | 2  | 3  | 4  | 5  | 6  | Total |
|------------------|----|----|----|----|----|----|-------|
| Shoulder         | 1  | 5  | 25 | 21 | 23 | 5  | 79    |
| Toes             | 2  | 0  | 25 | 0  | 0  | 5  | 37    |
| Back             | 1  | 13 | 40 | 40 | 45 | 13 | 151   |
| Knees            | 2  | 0  | 25 | 0  | 0  | 5  | 37    |
| Ankle            | 3  | 2  | 20 | 9  | 9  | 6  | 46    |
| Wrist            | 1  | 17 | 14 | 14 | 30 | 17 | 89    |
| Total            | 6  | 0  | 25 | 0  | 0  | 7  | 32    |
| Total            | 5  | 0  | 40 | 0  | 0  | 28 | 68    |

It should be noted that, as a rule, an expert is able to establish such parameters of exposure and susceptibility in the form of fuzzy intervals indicating the level of distinguishability.

In this case, any unfavorable outcome (UO) is standardly determined on the basis of the condition of exceeding the exposure (load or dose) over the susceptibility (strength or resistance, or the parameter of the effect) and, moreover, it is simplified to take into account that the protection monotonically weakens the effect.

The problem of determining the possible measure of the parametric prerequisite of the incident is solved as the problem of comparing two fuzzy numbers with triangular membership functions

\[ y = x_1 \lor x_2 \lor x_3, \quad \text{(1)} \]

\[ T = \{ \tau_i \}, \quad i = 1, 2, \ldots, I \text{[days]} \]

where respectively \( s \) and \( r \) — cores; and intervals \( \{ s - \Delta s, s + \Delta s \} \) and \( \{ r - \Delta R, r + \Delta R \} \) — fuzzy range \( \mu_s(x), \mu_R(x) \).

Moreover, the values \( \Delta_s, \Delta_R \) express the absolute errors in setting the parameters of exposure and susceptibility (Figure 1). In this case, the criterion for the excess of the fuzzy effect over the fuzzy susceptibility on the regions of existence of these parameters is presented in the form \( s > r \) s < r.
In the first approximation, under the assumption of a linear approximation of fuzzy parameters (in the least informative version of their obtainment), the dependence

\[ \pi'_L = 1 - \bar{z}b, \quad (3) \]

where \( \bar{z}b \) – reduced parametric safety margin (4):

\[ \bar{z}b = \frac{\bar{r} - \bar{s}}{\Delta r + \Delta s}, \quad (4) \]

in which \( \bar{r} \) and \( \bar{s} \) – respectively, the “cores” of fuzzy susceptibility parameters \( r \) and impact \( s \); \( \Delta_r \) and \( \Delta_s \) – “blurring intervals” of fuzzy parameters of susceptibility \( r \) and impact \( s \).

4. Modeling of unfavorable outcomes based on the excess criterion

In order to universalize the parametric modeling of any unfavorable outcomes on the basis of the exceeding criterion, a dimensionless representation of the parametric model of the incident was introduced using hygienic indicators such as MAC (maximum allowable concentration), MPE (maximum permissible exposure), SEL (safe exposure level) [2].

As a parameter of susceptibility, the pressure \( p \) (Pa) is taken when a press fragment hits an employee or when athletes are hit. The impact parameter during the hit is defined as the amplitude of mechanical stress \( \sigma \) (Pa) from the impact of the stamp on the worker or protection.

5. Selection and description of susceptibility parameters

From the textbook of Kapustin A.V. [3] bone fractures in the form of a crack in the inner bone plate (the beginning of the formation of a fracture) occur during impacts with a force of 900 to 1100 N. At a force of impacts from 7257.1 to 10689.6 N, along with cracks, bone fractures occur. And with an impact force of over 100,000 N, a lethal outcome occurs in almost 100% of cases. Based on these data, we will simplify the following "ruler" presented in Figure 2:

\[ p_1 = 1, \quad p_2 = 10, \quad p_3 = 100, \quad p, \text{kPa} \]

Figure 2. Simplified (deterministic) presentation of the values of the susceptibility parameters of the summit outcomes SO₁, SO₂, SO₃.

When the impact force is from 1 kPa to 10 kPa, the top outcome 1 occurs, the worker will have a finger fracture, i.e. disability injury.

With the magnitude of the impact force from 10 kPa to 100 kPa, the peak outcome 2 occurs, the employee will be injured with a long-term disability.

With the magnitude of the impact force from 100 kPa and above, the summit outcome 3 occurs, an accident with a fatal outcome occurs.
We represent these statements using the membership function of the fuzzy parameter of the employee’s susceptibility to impact at three levels (outcomes), where the cores and blur intervals according to Kapustin are approximately equal, respectively (5) (6):

$$\bar{r}_1 = 1, \quad \bar{r}_2 = 10, \quad \bar{r}_3 = 100 \quad \text{(kPa)} $$

$$\Delta_1 = 0.2; \quad \Delta_2 = 3; \quad \Delta_3 = 50 \quad \text{(kPa)}$$

**Figure 3.** Three-level representation of the susceptibility of an object and (or) subject to the impact of hazardous or harmful factors and corresponding outcomes (hazards).

Examples of fuzzy assessment of the risks of mechanical shock and the implementation of the three summit outcomes of an accident.

1) Analysis of the condition at the lower boundary. If the impact force is less than $r_1 - \Delta_1$, then there will be no fracture of the finger and the possible measure (PM) of SO1 is 0.

2) If the impact force is greater than $r_1$, but less than $r_2$, then the possible measure of SO1 is equal to 1, and the value PM of SO2 is calculated by formulas (5) and (6) and depends on the values of characteristics of the fuzzy parameters of the impact and susceptibility $r$, $s$, $\Delta_r$, $\Delta_s$.

For example, if $\bar{r}_2 = 10$, $s = \bar{r}_1$, then at $1) \Delta_r = \Delta_s = 0.5 (\bar{r}_2 - \bar{r}_1)$

We get, that $zb = 1$, and the value PM of SO2 ($\pi_{L_2}$) equals 0.

At 2) $\Delta_r = \Delta_s = 0.6 (\bar{r}_2 - \bar{r}_1)$ we get, that $zb = 0.83$, and the value PM of SO2 ($\pi_{L_2}$) equals 0.17.

3) If $s = 60; \quad \Delta_r = 20; \quad \Delta_s = 50 \quad \text{(kPa)}$, then PM of SO3 (at $r_3 = 100 \quad \text{kPa}$) equals $\pi_{L_3} = 0.43$.

4) If the exposure parameters were set absolutely precisely: $\Delta_s = 0$, $s = 0.9 \cdot \bar{r}_2$, then the problem of finding the PM of SO2 taking into account the relations $\bar{r}_2 = 10$ and $\Delta_2 = 3 \quad \text{(kPa)}$, can be solved either using the graph, Figure 3, or analytically $\pi_{L_2} = 1 - zb = 1 - 1/3 = 0.67$.

As you can see, the graphical and analytical presentation of the model of impact and susceptibility makes the procedure for calculating the possible measures of top outcomes according to the increasing degree of severity clear and allows you to avoid “gross” errors.

Thus, for the quantitative assessment of injuries that often occur, both in production and in sports, a parametric criterion of mechanical damage to an employee or athlete was developed and tested on the basis of the “impact - carrying capacity” model. The results obtained can be useful both for a comparative analysis of working conditions and sports, and for substantiating the methods and means of protection against the negative action of mechanical factors.

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