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DETERMINING THE PARAMETERS FOR CONNECTIONS AMONG THE ELEMENTS OF DESIGN OF VEHICLES IN TERMS OF ERGONOMICS AND CREW SAFETY

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Проведено дослідження робочих процесів системи «оператор – машина – зовнішнє середовище» сухопутних транспортних засобів з використанням розробленої математичної моделі.

Встановлено суттєвий вплив структури і параметрів зв'язків елементів конструкції на виконання вимог ергономіки та безпеки щодо екіпажів.

Доведено за результатами чисельного експерименту необхідність комплексного підходу на етапі проектування (модернізації) при визначенні параметрів об'єкта дослідження (як приклад розглянуто об'єкт з параметрами, близькими параметрами БТР-60…БТР-80).

Особливість комплексності полягає в одночасному виконанні вимог з позицій ергономіки та вимог безпеки. З позицій ергономіки регламентовані параметри плавності ходу, розміщення оператора (наприклад, водія) щодо органів управління машиною і, в цілому, в межах відділення управління з урахуванням його компонування. З позицій безпеки регламентовані параметри в разі підриву на міні.

Показано, що в межах методології прикладного оптимального проектування складних технічних систем можна вийти на реалізацію об'єкта дослідження (модернізацію), який задовольняє вимогам з позицій і ергономіки, і безпеки екіпажів.

Досягнення мети підтверджується результатами розрахунків у вигляді осцилограм (переміщень, швидкостей, прискорень, сил) робочих процесів трансформації силової дії збурюючого фактору на шляху від колісного рушія до оператора.

Математична модель дозволяє якісно і кількісно оцінити роль основних параметрів всього об'єкта і, зокрема, – пружно демпферних зв'язків на двох рівнях (перший рівень – підресорювання корпусу машини, другий рівень – підресорювання сидіння з оператором).

Числовий експеримент проведений з використанням методу Рунге-Кутта із змінним кроком з використанням оригінальної програми

Ключові слова: оператор, транспортний засіб, збурюючий фактор, підрив, ергономіка, безпека

1. Introduction

At present, construction (modernization) of wheeled and tracked vehicles, especially for military purposes, faces a contradiction in the requirements for ergonomics, requirements for safety of crew members (troops). According to the requirements for ergonomics, the parameters for fluctuations and vibrations, resulting from the interaction with a bearing surface, on the one hand, and the implementation of working operations of an engine and the transmission, on the other hand, must vary in certain limits. The natural oscillation frequency of a machine's body is regulated. Also regulated is the level of accelerations at the seats of a crew. Given this, engineers that design new equipment define the parameters for rigidity and damping of the cushioning system for the body of a machine. The same technique – by cushioning the engine and transmission elements, the seats for a crew and troops ensures the permissible level of vibrations (oscillations that have a relatively small amplitude and a not-too-low frequency). It is believed that human perception of riding in a car and the related fatigue are associated with the accelerations that person experiences during oscillations, as well as the repeated frequency of these accelerations. The simplest parameters that are very close to these perceptions are considered to be the natural oscillation frequency of a car's body. The necessary, but not always sufficient, condition for a ride smoothness is the magnitude of natural frequencies within 1.0...1.5 Hz (the frequency of disturbance at riding, usual and normal).

It is a relevant task to further advance the theory and practice of determining the rational structure and parameters of relations among elements of the system «operator – machine – external environment» for land vehicles with a comprehensive assessment for ergonomics and safety of crews.

The relevance of the study is also confirmed by the state of affairs regarding the experience and the nature of military activities. The radical change in the character of war, from the positional to the local, changed the way for AAV development. The local character of warfare implies frequent change of dislocations, quick displacement of troops and weapons, fulfilling logistical tasks on material and technical provision. To solve these tasks, it is more suitable to employ light armored vehicles than the capabilities of heavy military machinery. An analysis of ATO experience regarding military personnel injuries proves that the largest share accounts for injuries in the explosions. A prerequisite for the preservation of the body's integrity, the main factor for damage is the acceleration (amounting to 100...500 g at the driver's seat).

At present, there are many manufacturers of military equipment and dual-use technology protected against mines. Specifically, the vehicles that are protected against mines include: Casspir Mk6 (South Africa), Caiman MTV (USA), Golan (Israel and USA), Dingo 2 (Germany), Tiger-M (Russia), Typhoon-U (Russia) and others.

In 2017, the Ukraine's armed forces adopted the armored vehicle «Kozak 2». To increase the probability of survival during landmine explosion, the engineers applied a module principle to fabricate a V-shaped bottom, to absorb and dissipate the energy of part of an explosion (acts together with a multilayered floor). The level of protection against mines is confirmed by actual explosions – using the mines that are equivalent to 6 kg of TNT (under a wheel and under a bottom). In addition, the seats that are protected against mines are installed (the seats for troops are suspended, attached to the top part of a body). In this regard, one can conclude that among the most serious threats to armored vehicles (AV) in the most typical local conflicts are mines and improvised explosive devices (IED). More than half the losses of military equipment are associated with landmine explosions and IED. Ensuring high resistance against mines requires a comprehensive approach, which would include both the component and structural, «circuit», solutions. A comprehensive approach also implies using specialized equipment, particularly energy-absorbing seats for a crew.

Within the framework of the applied procedure for optimal design of complex engineering systems by using a comprehensive approach, designers of new equipment have to deal with the incompatibility of rational solutions in terms of all requirements. Significant difficulties are particularly due to such an attribute of the examined object as the existence of disturbing factors with a wide range of frequencies and amplitudes. There are disturbances within a workflow between the engine that interacts with the irregularities of a supporting surface when moving over crossed terrain and working processes of the engine and transmission during transformation of a force flow from the engine to the propeller. A special role belongs to disturbances related to the boundary conditions for motion stability, suspension breakdowns, and working processes during explosions of landmines and improvised explosive devices.

Using the applied procedure for optimal design implies the existence of an adequate mathematical model of working processes related to the examined object. As regards the safety of crews, the defining process is the transformation of a force action of the pulse load applied to a first wheel along the motion of a machine when driving over a contact mine (the most likely situation for contact mines). This working process is the most dangerous in terms of consequences for humans. The estimation parameter is considered to be the magnitude for the acceleration of an operator together with a seat in the vertical plane.

Ergonomics in the dynamics is estimated based on the ride smoothness parameters and the position of a driver relative to machine controls, as well as the adjacent equipment, under conditions of motion over crossed terrain. The ride smoothness, in particular, is used to standardize the magnitudes for natural frequency of oscillations, as well as the accelerations of a machine's body (under forced vertical and angular displacements) at the place of a seat with the driver.

In the design process, parameters for ride smoothness are defined based either on the simplified analytical dependences or on the calculations, by using numerical methods, of the oscillations of a machine's body (at vertical and angular displacements).

A driver's position relative to machine controls and the adjacent equipment is estimated by the displacement in the vertical plane relative to the body of the machine statically (under its own weight) and dynamically (during landmine explosion).

2. Literature review and problem statement

International Organization for Standardization (ISO) defines the permissible limits for the acceleration of a seat for the most sensitive (in terms of human's physiology) frequency range of 4...8 Hz. For single impact loads, the acceptable limit is considered to be the acceleration not exceeding 3g [1]. The complex character of oscillations within a vehicle is clearly seen on records of oscillations, for example, vibrograms or accelerograms. A curve of oscillations is divided into parts: oscillations and vibrations. Such a distribution is conditional and may have a different base. In terms of physiology, one can assume that oscillations are perceived by human body separately, while vibrations – merged. The limit of a vibrational sensitivity by a human is about 18...23 Hz. Given this, it is conventionally considered that oscillations with frequencies above 17 Hz are vibrations. As regards the nature of oscillations, the oscillations at frequencies to 17 Hz are associated with the oscillations of the body and wheels on the elastic elements of the suspension and propeller (wheeled or tracked). The nature of vibrations is associated with frequencies above 17 Hz (vibrations relate to working processes in the engine, transmission, body, etc.). It is obvious that the means to eliminate oscillations and vibrations are different [2]. A special place is occupied by single impact loads that occur at suspension breakdowns and explosions on explosive devices. The relative frequencies of these disturbing factors significantly exceed the frequencies of disturbance factors associated with oscillations and vibrations. This applies to the magnitudes of acceleration both for the case of a suspension breakdown in the process of machine motion (vertical accelerations at the driver's seat reach 8...10 g [3]) and during landmine explosion.

The statistics of injuries received in the course of military activities testify to that the main parts of the body subject to danger are legs, spine, head. Specifically, injuries to the extremities, received by soldiers from the United States during operations in Iraq and Afghanistan, account for up to 40 % [4, 5]. Detailed studies into the permissible dynamic vertical impacts on humans date back to World War II, with the advent of ejection seats [6, 7]. In aviation, during catapulting and emergency landing of planes and helicopters, there are large vertical overloads (14...30 g) at a relatively small time of action (60...180 ms) [8–11]. Such overloads lead to injuries to a crew (primarily the spine, which is most vulnerable under vertical overloads).

The body of an auto-armored vehicle (AAV) is almost instantly gaining vertical speed [14, 15] and, without proper protection, the crew is subject to serious injuries of the spine. It is known that a qualitative change in the designation of military vehicles, against a background of intensive development of the means for detecting and destroying potential enemies, predetermines substantial expansion and enhancement of the tactical-technical requirements. In the long term, the required average speed of vehicles should increase (from 20...30 to 40...45 km/h), while the mass of an explosive at which the life and health of a crew can be saved must increase by 10...15 times, from 0.7 to 10...12 kg. It should be noted that when moving over crossed terrain, all other conditions being equal, the decisive indicators are those for ride smoothness, specifically the existence of motion modes for suspension breakdowns under certain conditions [1].

Resolving this issue is directly linked to a vehicle's running system, in particular, its parameters for rigidity, damping, inertia, kinematics. It is known that military activities of the Soviet troops in Afghanistan involved tanks T-55 and T-62, infantry combat vehicles BMP-1 and BMP-2, as well as the armored personnel carriers (BTR-60 to BTR-80).

An analysis of combat injuries revealed that explosions of mines and landmines at one or another place under a machine depends on the means for their detonation.

Mines and landmines with pressure action typically explode under the front wheels (tracks) [16]. Solving the tasks requires a comprehensive approach for two priorities: considering the reaction of an object to disturbance when implementing a transporting function and the function of crew protection against explosions. The reactions are interrelated and depend on many parameters and properties of an object, as well as disturbing factors.

Approaches and solutions to a series of problems in this field using the numerical implementation of operational processes (yielding the parameters for estimation) are described in papers [15, 17–19]. Studies [15, 18] addressed the issues on simulating a detonation when driving over a mine and on estimating the degree of possible damage to a crew. Articles [17, 19] examined the response of the examined object to a change in the motion regimes.

It should be noted that under all other conditions being equal, the magnitude of accelerations significantly depends on the structure and parameters of arranging the seat within the body of a machine. The second generation of energy-absorbing seats for a helicopter already had a variable force to enable them [20, 21]. These seats were constructed with the use of two types of energy-absorbing elements: rolling the wire and turning out the pipe. However, it would not suffice to provide for the permissible level of acceleration. It is necessary to ensure the specific positioning of an operator relative to the body of machines. In other words, positioning in terms of ergonomics is the position relative to machine controls, weaponry, and, in general, relative to any equipment. In terms of ergonomics, according to requirements for ride smoothness – the amplitude and frequency of oscillations, etc.

At present, commonly applied are the energy-absorbing seats based on various design solutions that attach them to the body of a machine. In particular, attaching a seat to the upper part and sides of the machine, with the required attachment elements, which include a sufficient number of safety belts, slings for legs, limiters of head movements in lateral directions. The main parameters that define the operational efficiency of an energy-absorbing element is its performance speed and the magnitude of the force of its triggering. The force of triggering is limited by the permissible load on human body. The maximum stroke of an element is defined by the dimensions of an operator's workplace, by constraints in its assembly.

At present, there are no publications that report a comprehensive approach in terms of ergonomics and crew safety, particularly for light armored vehicles. The reason for this is adherence to a traditional approach – without regard to the transformation of a force flow from a wheel to an operator during explosion. The transformation occurs under the influence of parameters both for chassis and an operator's connection with a machine's body. These parameters affect both ergonomics and safety. On the other hand, the reason is the complexity of the examined object in terms of its manifestations of interaction with the external environment. In addition, there are no studies that could quantify the integrated estimate for the parameters of operational processes. That allows us to argue about the relevance of our research in this field.

3. The aim and objectives of the study

The aim of this study is to solve a problem related to a comprehensive approach to the subsystem «operator – workplace – machine» by using a light weight AAV (the machine that is close in parameters to BTR-60...BTR-80) as an example. A comprehensive approach implies meeting simultaneously the requirements for ergonomics and safety for crew members within the framework of the applied procedure for optimal design of complex technical systems.

To accomplish the aim, the following tasks have been set:

– to further advance an adequate mathematical model of the examined object for application in the design of a new product, or when upgrading an existing one, for defining the structure and parameters of elastic damping links in the structure's elements;

– to conduct a numerical experiment that would yield the parameters for evaluation (of strength, displacement, velocity, acceleration) based on oscillograms of operational processes;

– to devise recommendations regarding the parameters for an elastic damping connection between an operator's seat (using a driver as an example) and the body of a machine.

4. Materials and methods for a study into determining the parameters for a connection between an operator's seat and the body of a machine

4. 1. Mathematical model of the examined object

To derive a comprehensive assessment in terms of ergonomics and safety of crew members, a mathematical model must take into consideration the main features of the natural object, specifically the non-linear character of elastic damping connections. The nonlinearity is associated in particular with the kinematics of the structure's elements at their relative displacements (wheels relative to the body of a machine, wheels relative to a supporting surface, seats with members of the crew relative to a machine's body).

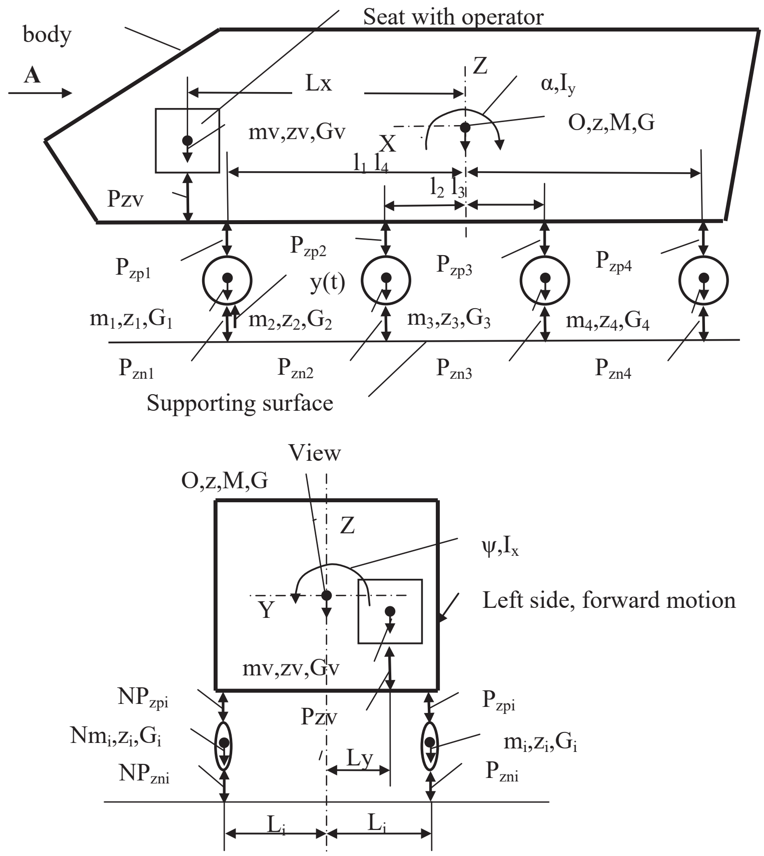

Fig. 1. Estimated scheme of the examined object

The special features also include the modes of motion when wheels detach from a supporting surface, suspension breakdowns. Suspension breakdowns occur in a contact with stroke limiters. When in contacts with stroke limiters, their elastic deformation within certain limits takes place, to the point when the elastic stroke is exhausted while a subsequent contact with the cushioned and non-cushioned mass becomes significantly (by several orders of magnitude) more rigid.

To achieve the estimation parameters – the magnitude of acceleration of an operator (a member of the crew or troops), their displacement relative to the body of a machine, the frequency of these parameters – one should acquire oscillograms of the operational processes for the examined object in dynamics. In particular, information on the transformation of a pulse force action during landmine explosion (from the point a force was applied to the seat with an operator).

Next, based on an analysis of results, one should make a decision on the existence of a possibility of practical implementation based on a set of parameters for ergonomics and safety of an operator. To find out whether there is a solution by changing the parameters for rigidity and damping the elastic damping connections.

In case it is impossible to solve the problem based on a set of parameters for ergonomics and safety of an operator, one should consider the possibilities to change the structure at two levels related to cushioning. It is possible to implement changes both at the level of connections «wheels – machine's body» and at the level of connection «machine's body – operator».

The estimated scheme of the examined object is shown in Fig. 1.

The toolset used for solving a set of practical problems was the constructed mathematical model of the examined object based on a system of second order differential equations (1):

$$M \cdot \ddot{z} = \sum_{i=1}^{4} P_{zpi} - \sum_{i=1}^{4} NP_{zpi} - G + Pzv,$$

$$I_y \cdot \ddot{\alpha} = \left(\sum_{i=1}^{4} P_{zpi} - \sum_{i=1}^{4} NP_{zpi} \right) \cdot l_i + Pzv \cdot Lx,$$

$$m_1 \cdot \ddot{z}_1 = P_{zn1} - G_1 - P_{zp1} + y(t),$$

$$m_2 \cdot \ddot{z}_2 = P_{zn2} - G_2 - P_{zp2},$$

$$m_3 \cdot \ddot{z}_3 = P_{zn3} - G_3 - P_{zp3},$$

$$m_4 \cdot \ddot{z}_4 = P_{zn4} - G_4 - P_{zp4},$$

$$Nm_1 \cdot N\ddot{z}_1 = NP_{zn1} - NG_1 - NP_{zp1},$$

$$Nm_2 \cdot N\ddot{z}_2 = NP_{zn2} - NG_2 - NP_{zp2},$$

$$Nm_3 \cdot N\ddot{z}_3 = NP_{zn3} - NG_3 - NP_{zp3},$$

$$Nm_4 \cdot N\ddot{z}_4 = NP_{zn4} - NG_4 - NP_{zp4},$$

$$I_x \cdot \ddot{\psi}_x = \left(\sum_{i=1}^{4} P_{zpi} - \sum_{i=1}^{4} NP_{zpi} \right) \cdot L_i + Pzv \cdot Ly,$$

$$mv \cdot \ddot{z}_v = Pzv + Gv, \qquad (1)$$

where M, G, I_y, I_x are the mass, weight, and moments of inertia for the cushioned body relative to the longitudinal OY and transverse OX axes in the coordinate system $OXYZ$ originating from O in the center of masses; mv, Gv are the mass and weight of the seat with an operator; $\ddot{z}$, $\ddot{z}_1$, $\ddot{z}_2$, $\ddot{z}_3$, $\ddot{z}_4$ are the linear accelerations in the direction of the OZ axis of the center of masses of a body and wheels1, 2, 3, 4 along the motion direction of a machine; $\ddot{z}_v$ are the linear accelerations in the direction of the OZ axis of a seat with an operator; $\ddot{\alpha}$, $\ddot{\psi}_x$ are the angular accelerations of a machine's body relative to the longitudinal OX and transverse axis OY, respectively; P_{zpi} is the effort between a wheel and a machine's body caused by the action of elastic and damping forces of the suspension; Pzv is the effort between a machine's body and a seat with an operator caused by the action of elastic and damping forces in the connection between the body and the seat; l_i are the distances in the direction of the OX axis from the center of mass of the cushioned body to the axis of the i-th wheel (along the machine); L_i are the distances in the direction of the OY axis from the center of mass of the cushioned body to the i-th wheel (across the machine); Lx, Ly are the distances of a seat in the direction of the OX, OY axes from the center of mass of the cushioned body; m_i, G_i are the mass and weight of the non-cushioned parts of the chassis; P_{zni} are the efforts between a supporting surface and the wheel of the i-th suspension; $y(t)$ is the force from the effect of explosive gases when a mine explodes under the first wheel on the left side along the machine's motion.

The letter N in differential equations denote forces on the machine's right side along its motion.

In the mathematical model, the magnitudes for efforts P_{zpi}, P_{zni} are predetermined by the characteristics of the elastic-damping connections between wheels and, respectively, a machine's body and a supporting surface, and efforts Pzv – between a set and the body of the machine. These characteristics are essentially nonlinear (depend on the structure and settings for guiding elements; elastic elements – springs, stroke limiters; damping elements – shock absorbers). The nonlinearity is also due to the existence of wheels detaching from the supporting surface under certain conditions.

Within the framework of research, we introduced to the mathematical model an elastic damping relation between a seat with an operator and the body of a machine with a constraint for effort Pzv (the structure of the connection implies a friction element of dry friction). This extension of the mathematical model takes into consideration the peculiarity of disturbance factors during explosion (a pulse character of great intensity).

Such a solution is simple in its structure and, importantly, ensures the required performance speed in terms of a response to the pulsed disturbance.

It is known that the most common suspensions for assemblies that are mounted on a body (particularly, engines) include rubber (various silent blocks that differ in design). Within the framework of the current research, the mathematical model was supplemented with such an elastic damping connection.

However, in this case it is necessary to take into consideration the features of change in the internal friction inside rubber depending on the parameters for disturbance factors over the entire range (of frequencies and amplitudes).

Paper [2] noted that the intramolecular friction occurs mainly in rubber elastic elements. In this case, it is believed that the attenuation in rubber is proportional to the velocity of oscillations. However, a coefficient of non-elastic resistance is not constant, but varies inversely proportionally to the frequency of oscillations. Therefore, when one changes frequency over a wide range, it is impossible to ensure effective attenuation. In addition, the intramolecular friction inside rubber cannot create a significant magnitude for attenuation (in rubber suspensions, $\psi=0.1$ on average).

Intramolecular friction in rubber depends on its composition; for example, at a large content of soot, it can be, in line with a law on change, the same as constant friction. Specifically, for a tyre, internal friction depends on a series of factors, including the tyre design, the number of cord layers, the internal air pressure inside a tyre, the amplitude of its deformation (relative attenuation is on average $\psi=0.05...0.106$.

Paper [22] noted that is not always possible to take adequate measures of protection against excessive displacements caused by impact loads and loads caused by the acceleration of motion without compromising the efficiency of insulation provided by a suspension.

Based on data from studies [2, 22], the damping parameters are accepted taking into consideration the character of a material used. In our case of the internal friction inside rubber, which is taken into consideration through the partial relative coefficients of attenuation – coefficients of aperiodicity within a range of $\psi=0.05...0.106$. In this case, damping parameters are determined considering the frequency of disturbance in the case of oscillations or vibrations, and the relative frequency of disturbance in the case of a single pulse, determined on the basis of its duration.

For the case of a pulse action, coefficient cy for the non-elastic resistance (for the elastic material whose damping properties greatly depend on the frequency of a disturbance factor, predetermined by the peculiarities of internal friction inside the material) is derived from formula:

$$cy = 2\cdot\psi\cdot\omega\tau\cdot mv, \qquad (2)$$

where a conditional frequency of pulse disturbance $\omega\tau = 2\pi/T$ ($T = 2\tau$, where τ is the pulse duration).

For the case of a pulse action, but for the elastic material whose damping properties slightly depend on the frequency of disturbance factors (oscillations, vibration), the coefficient cy for the non-elastic resistance is determined from formula:

$$cy = 2\cdot\psi\cdot\omega mv\cdot mv, \qquad (3)$$

where partial natural oscillation frequency $\omega mv = \sqrt{ky/mv}$ (ky is the rigidity of a connection).

Force of disturbance $y(t)$ is introduced in line with exponential dependence [15], constructed with the application of the theory of detonation of various hurdles under different conditions for explosion [23, 24].

The time of action of excessive pressure during explosion is determined from formula:

$$\tau = 0.0015\cdot\sqrt{Rz}\cdot\sqrt[6]{Qz} \ \ [20], \qquad (4)$$

where Rz is the distance from the point of explosion to the place of action of explosive gases in (m), Qz is the power of a charge equivalent to TNT (kg).

Results of the experiments (*applying the authentic software*) in the form of oscillograms, acquired by applying a numerical method by Runge-Kutta, at a variable step, are shown in Fig. 2–5. All the experiments were carried out at the same factor of disturbance (Fig. 2, *a*).

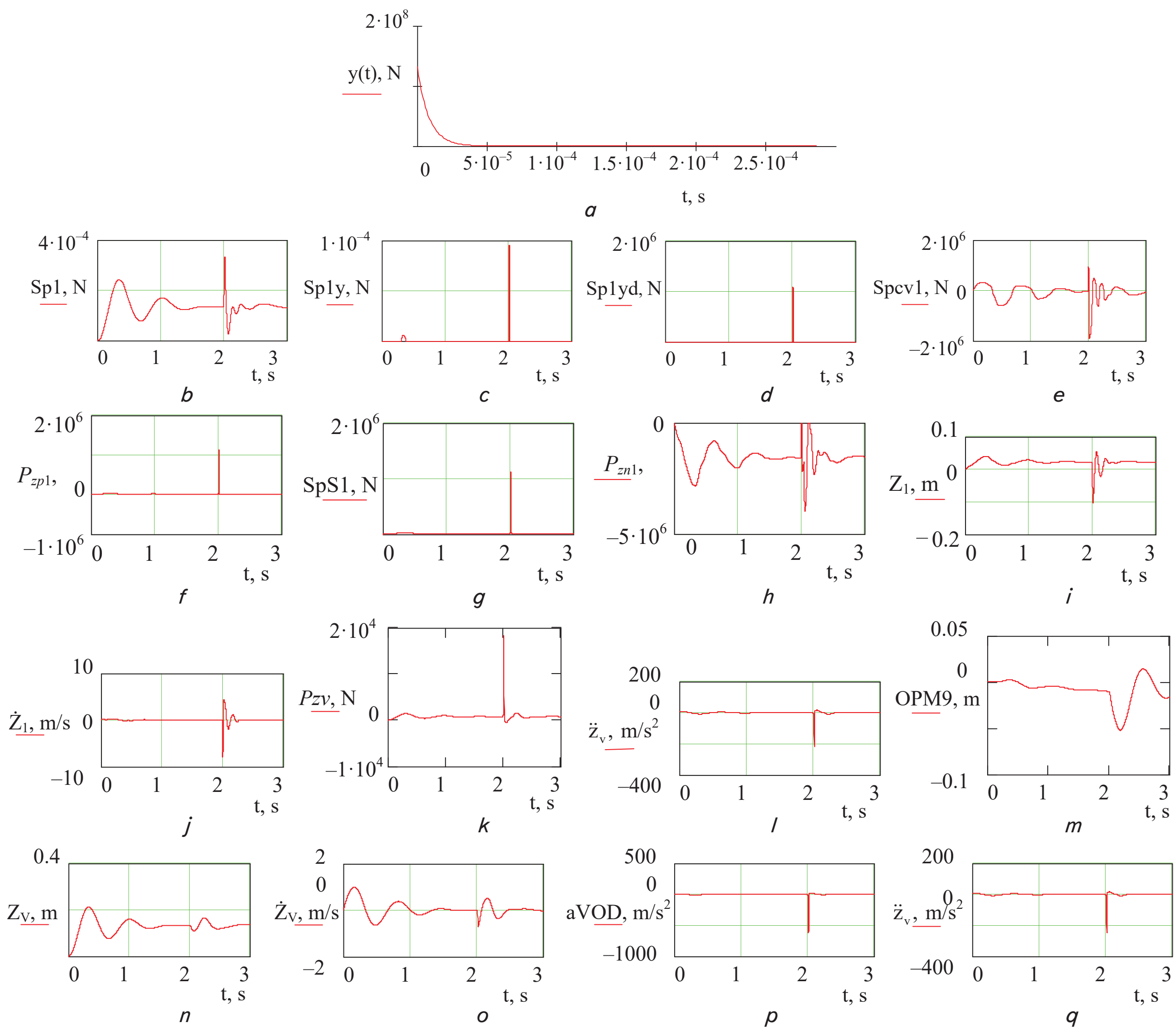

Fig. 2. Oscillograms of parameters for the force flow (forces, displacements, velocities, and accelerations) from a wheel to an operator (parameters for the elastic damping connection between a seat and a body: ψ=0.05; $\omega\tau$=1.096·10^4 rad/s; *cy*=8.764·10^4 N·s/m) without a possibility for a seat to slide relative to the body: *a* – *y*(*t*)) – efforts of a pulse character from an explosion; *b, c, d* – Sp1, Sp1y, Sp1yd are, respectively, the elastic components of efforts P_{zp1} in a suspension; *e* – Spcv1 is the damping component of efforts P_{zp1}; *f* – P_{zp1} is the elastic damping effort in a suspension between the first wheel and a machine's body; *g* – SpS1 is the total elastic component of efforts P_{zp1}; *h* – P_{zn1} is the effort in a contact between a wheel and a supporting surface; *i, j* – Z_1, $\dot{Z}_1$, respectively, are the displacement and a wheel's speed; *k* – *Pzv* is the elastic damping effort between a seat and a body; *l* – $\ddot{z}_v$ is the operator's acceleration; *m* – OPM9 is the displacement of an operator relative to the body; *n, o* – Z_V, $\dot{Z}_V$, respectively, are the absolute displacements and velocities of an operator; *p* – aVOD is the acceleration of a body at the site of an operator; *q* – $\ddot{z}_v$ is the operator's acceleration (at: ψ=0.1, $\omega\tau$=1.096·10^4 rad/s; *cy*=1.753·10^5 N·s/m)

The initial data on the mass and dimensions of the examined vehicles accepted for the research as an example are the parameters that are close to modern armored personnel carriers. It was accepted: the complete mass of a machine is 12.596 kg (cushioned mass – 10.380 kg, non-cushioned – 2.216 kg), the base of a machine is 4.4 m, gauge – 2.38 m, the body's length is 7.85 m, the body's height is 1.36 m, the body's width is 2.38 m. The mass of a driver with a seat is 80 kg.

The experiment was conducted based on the following algorithm (it has four characteristic states over time):

– 1 – at t=0, the machine is under a suspended mode (no contact between the wheels and the supporting surface);

– 2 – at t>0, under the action of a gravity force there are contacts between the wheels and the supporting surface; there begins the process of free oscillations that completely decay at t=2 s;

–3 – at t=2 s, effort $y(t)$ is applied to the first wheel on the left side along the forward motion (Fig. 1);

– 4 – at t>2 s, there are forced oscillations in a combination with free oscillations.

4. 2. Results of research based on the oscillograms of operational processes for the following parameters: displacement, speed, acceleration, force

Fig. 2 shows oscillograms based on calculating efforts in the elastic-damping connections of the examined object and other parameters for operational processes when a landmine explodes under a first wheel on the left side of the machine.

In terms of the structure and parameters of the elastic damping connections the examined object is also close to modern armored personnel carriers.

The wheel is exposed to a factor of disturbance (effort $y(t)$) of the pulsed character (Fig. 2, *a*).

An elastic connection between a wheel and a body structurally consists of three elastic components. The first component is the torsion whose elastic resistance acts along the entire possible stroke of the suspension. The second component is the elastic stroke limiter (rubber-based), whose resistance appears at a stroke of the suspension that is greater than the static stroke by a certain predefined magnitude. The third component is the elastic resistance associated with relatively significantly greater rigidity of the stroke limiter, which follows the destruction of rubber.

The oscillograms for efforts Sp1, Sp1y, Sp1yd correspond to elastic components 1, 2, 3 (Fig. 2, *b–d*). Damping resistance is created by a hydraulic telescopic shock absorber with different supports for the forward and reverse motion. The oscillogram is for damping effort Spcv1 (Fig. 2, *e*), and for the total elastic damping P_{zp1} (Fig. 2, *f*).

The total elastic damping effort is slightly different, towards a larger value, than the total SpS1 elastic effort (Fig. 2, *g*). During an explosion, the wheel is detached from a supporting surface, as demonstrated by the oscillogram (Fig. 2, *h*) for effort P_{zn1} in a contact between the wheel and this surface (during an explosion, the effort twice accepts a null value). The wheel at explosion bounces by magnitude Z_1 (Fig. 2, *i*) at velocity of magnitude $\dot{Z}_1$ (Fig. 2, *j*).

Elastic damping effort *Pzv* (Fig. 2, *k*) that acts on the seat with an operator causes the acceleration of the operator $\ddot{z}_v$ (Fig. 2, *l*). In this case, there is a relative displacement OPM9 of the operator and the body (Fig. 2, *m*) under absolute displacements Z_V (Fig. 2, *n*) and the speed $\dot{Z}_V$ (Fig. 2, *o*) of the operator.

The above parameters for the displacement, speed, and acceleration of an operator are valid while mounting his seat in place of the driver. A driver's seat is located inside the body of a machine in the region of a first wheel on the left side, the acceleration aVOD at a driver's seat (Fig. 2, *p*).

Fig. 3 shows oscillograms of the calculations based on certain parameters (selected) at another magnitude for coefficient *cy* of non-elastic resistance, determined without regard to changes in the internal resistance of rubber when one changes the frequency of disturbance.

Fig. 4, 5 show the selected information based on the calculation results to illustrate the impact of changes in the design of an elastic damping connection between a seat and a body (introduction of the frictional element of dry friction to limit effort *Pzv*). The force of friction is taken such that it exceeds the weight of an operator with a seat by three times.

Based on the results from the first experiment (Fig. 2), it was established that during an explosion the wheel is detached from a supporting surface. The fact of detachment is demonstrated by the oscillogram (Fig. 2, *h*) for effort P_{zn1} in a contact between a wheel and this surface (at explosion, the effort twice accepts a null value).

A wheel during an explosion bounces by magnitude Z_1=0.153 (Fig. 2, *i*) and achieves speed $\dot{Z}_1 = 7.838$ m/s (Fig. 2, *j*). As regards the elastic damping effort, which acts on a seat with an operator (the total weight of the seat with an operator is 784.8 N), during an explosion the effort amounts to $Pzv=1.839\cdot10^4$ N (Fig. 1, *k*), and the acceleration of an operator $-\ddot{Z}_v = 220.062$ m/s^2 (Fig. 2, *l*).

The relative displacement of an operator and a body (Fig. 2, *m*) OPM9 reaches 0.052 m (static draught of the seat is 0.0156 m). The above parameters for the displacement, speed, and acceleration of an operator are valid when his seat is at a driver's place (in the region of the first wheel on the left side of a machine). At this place, the acceleration aVOD of a machine's body reaches 614.533 m/s^2 (Fig. 2, *p*).

The second experiment was conducted at another magnitude for coefficient *cy* of non-elastic resistance (Fig. 3), determined without regard to changes in the internal resistance of rubber when one changes the frequency of disturbance. As was accepted earlier, rubber in the design serves as an elastic and damping element.

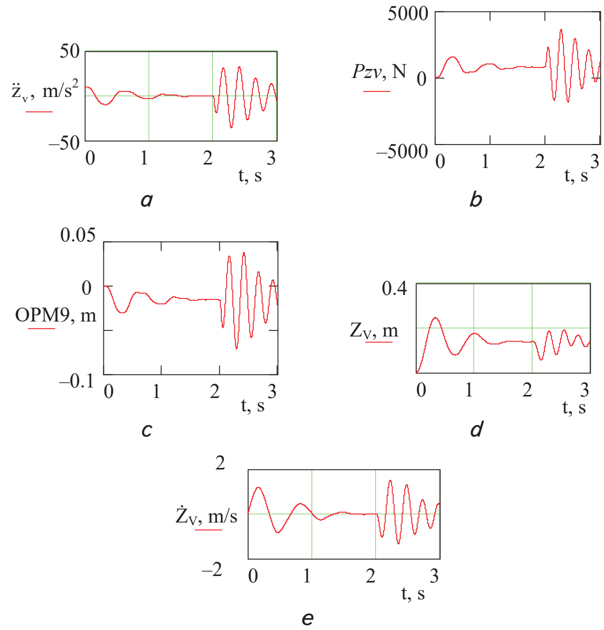

Fig. 3. Oscillograms (selected) for the parameters of a force flow (forces, displacements, velocities, and acceleration) from a wheel to an operator (parameters for the elastic damping connection between a seat and a body: ψ=0.05; ωmv=25 rad/s; *cy*=200 N·s/m) without a possibility for a seat to slide relative to the body

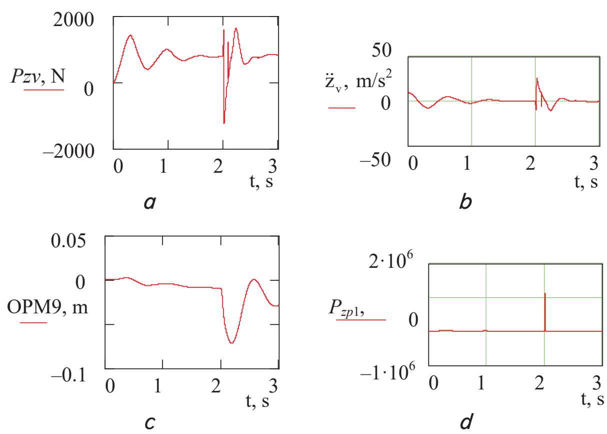

Fig. 4. Oscillograms (selected) for the parameters of a force flow (forces, displacements, velocities, and acceleration) from a wheel to an operator (parameters for the elastic damping connection between a seat and a body: ψ=0.05, $\omega\tau=1.096\cdot10^4$ rad/s; *cy*=$8.764\cdot10^4$ N·s/m) with a possibility for a seat to slide relative to the body

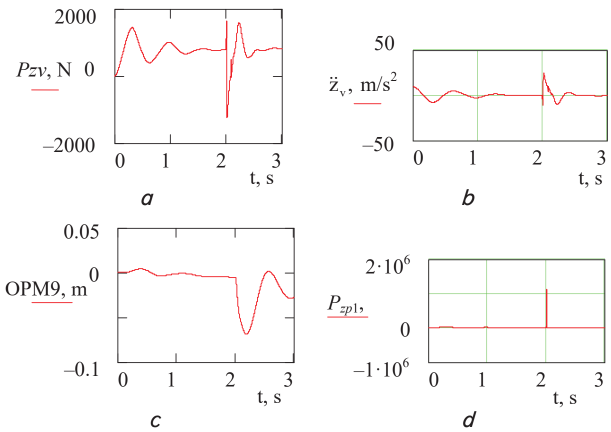

Fig. 5. Oscillograms (selected) for the parameters of a force flow (forces, displacements, velocities, and acceleration) from a wheel to an operator (parameters for the elastic damping connection between a seat and a body: ψ=0.1, $\omega\tau$=1.096·10[4] rad/s; cy=1.753·10[5] N·s/m) with a possibility for a seat relative to the body

Almost at the same accelerations aVOD (620.892 m/s^2 instead of 614.533 m/s^2) at an operator's (driver's) seat the maximum accelerations $\ddot{z}_v$ for the operator amount to 35.388 m/s^2 (Fig. 3, *a*). These accelerations are significantly less than similar accelerations in the first experiment (by 6.21 times), but still exceed the permissible accelerations in terms of ride smoothness of 3g. Accordingly, there is a significant decrease in efforts *Pzv* between a body and a seat (Fig. 3, *b*) – by 5.08 times. In this case, there is an increase (by 1.365 times) in the relative displacements OPM9 of an operator and a body (Fig. 3, *c*). There is also an increase in the absolute displacements Z_V of an operator (Fig. 3, *d*) and his speed $\dot{Z}_V$ (Fig. 3, *e*).

The results from the third (Fig. 4) and fourth (Fig. 5) experiments show that when at the introduced constraint for force *Pzv* the accelerations $\ddot{z}_v$ of an operator reach 25.288 m/s^2 (ψ=0.05)...25.207 m/s^2 (ψ=0.1) and do not exceed the permissible accelerations of 3g. In this case, when ψ increases the force *Pzv* increases as well, while relative displacements OPM9 decrease. When rubber is used in practice as an elastic damping element with a possibility to limit the force *Pzv* structurally, the impact of intramolecular friction on the operational process is negligible. The constraint for force *Pzv* is accompanied by the external dry friction at relative displacements of the seat and body.

The magnitudes for natural oscillation frequencies (without taking into consideration the dissipation of energy) of a machine's body in the vertical direction (linear – 1.483 Hz, longitudinal angular – 1.26 Hz, transversely angular – 2.92 Hz) and an operator – 3.98 Hz. From the standpoint of ergonomics (in terms of ride smoothness) these frequencies are within those recommended in practice.

4. 3. Recommendations concerning the parameters for an elastic damping connection between an operator's seat (using a driver as an example) and the body of a machine

Based on the results from the current study, it is recommended to introduce a constraint for the elastic damping effort *Pzv* in the connection between a seat and the body of a machine. In terms of design, it is recommended to implement the constraint by introducing a frictional element of dry friction in series with the elastic damping element. The result would mean meeting the conditions for ergonomics (in terms of ride smoothness) and safety (limiting overloads on operator).

5. Discussion of research results based on the oscillograms of operational processes according to the parameters for: displacement, speed, acceleration, force

The results obtained were derived based on the application of the constructed adequate mathematical model of operational processes of the examined object. The mathematical model makes it possible, based on a numerical experiment, to obtain an estimate for ergonomics and safety. A comprehensive estimate contributes to making decisions on determining the rational structure and parameters for the elastic damping connections among the elements of design.

The merits of the proposed integrated approach include taking into consideration the features of the design of elastic damping connections at two levels. The first level is «supporting surface – wheels – body». The second level is «a machine's body–an operator's seat». It is known that from the standpoint of ergonomics it is desirable to obtain a minimally possible rigidity of suspension. Consequently, the low frequency of natural oscillations of a machine's body. A positive consequence is decreasing the accelerations of a driver under any disturbances at the first level, subject to certain constraints. At relative displacements of a wheel and a body until a suspension breakdown and the emergence of the mode to limit the stroke of a suspension at a significantly greater rigidity than predicted.

Therefore, under this mode, an operator's overload, all other conditions being equal, would increase. An increase in the overload grows in proportion to a lower rigidity of the suspension. This is due to an increase in the relative speed of a wheel and body under the mode of a «hard» constraint for stroke. Additionally, from the standpoint of ergonomics, reducing the stiffness of suspension could lead to the appearance of a seasick mode.

Thus, there is a contradiction between the requirements for ergonomics and safety. The way out is a compromise for both requirements – along the path of determining the rational structural parameters according to the methodology of applied optimal design. Searching for rational parameters and structural solutions for elastic damping connections at both levels.

The problem has been resolved by limiting the maximum effort within the connection between a machine's body and an operator's seat at explosion.

6. Conclusions

1. The mathematical model has been further advanced, which makes it possible to solve practical tasks employing a comprehensive approach in terms of ergonomics and safety of crew members in the process of design (modernization) of an article. The development implies considering additional features of operational processes of the examined object:

– a substantial increase in the rigidity of connections at the level «wheels – a machine's body» when the elastic stroke of suspension is exhausted;

– a substantial increase in the non-elastic resistance in a connection at the level «a machine's body – operator» at explosion.

2. The results from a numerical experiment that yielded the parameters for estimation (force, displacement, velocity, acceleration) give grounds to argue about the qualitative and quantitative adequacy of the mathematical model and the possibility to apply it in practice. The proof is the information based on oscillograms for the operational processes of a machine that is close in its parameters to modern armored personnel carriers.

3. It is recommended to introduce a constraint for the magnitude of effort *Pzv* between a machine's body and an operator. The constraint is to be implemented by introducing a possibility, based on the structure of a connection between a seat and a machine's body, to enable relative displacements of the seat and the body, accompanied by external dry friction.

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