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Decision-making regarding the application of any new structure at the design stage requires in practice that it should be compared with the existing one by many indicators. A special feature of the new design of hydro-pneumatic suspension is the existence of movable connections (screw and splined) as parts of the hydropneumatic element. The presence of structural friction in movable connections requires, in particular, an assessment of the impact of this friction on the process of oscillations when moving through crossed terrain based on comparative analysis. The comprehensive estimate chosen for comparison includes operational properties in terms of ergonomics (smooth movement) and adhesion to the support surface (effort in the contact of wheels with the support surface).

The results of a theoretical study involving a vehicle with parameters (weight, dimensions) close to armored personnel carriers BTR70, BTR80, but with hydropneumatic suspensions, demonstrated that when driving on crossed terrain with speeds up to 65 km/h there is a significant reserve in terms of ergonomics. Regardless of the presence (absence) of structural friction, at friction coefficients of up to 0.085. When moving on the surface with large irregularities, the reserve for the maximum allowable (3 g) acceleration in a driver seat is 4.708 times (there is no structural friction) and 3.768 times (structural friction is present). When moving on the surface with small irregularities, the reserve for the maximum permissible (0.5 g) acceleration in a driver seat is 2.093 times (there is no structural friction) and 2.616 times (structural friction is present).

Under the most dangerous modes of movement (at the highest speeds) when driving over small irregularities, the presence of structural friction has a positive effect both in terms of ergonomics and stability. Thus, when driving at a speed of 65.679 km/h, the minimum clutch margin is 1.4 times greater, and the acceleration is 1.249 times smaller

Keywords: vehicle, operational properties, smooth movement, adhesion to the support surface, oscillations, suspension, structural friction

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COMPREHENSIVE ASSESSMENT OF THE INFLUENCE OF STRUCTURAL FRICTION IN A VEHICLE SUSPENSION ON ITS PERFORMANCE

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1. Introduction

The construction (modernization) of wheeled and tracked machines for various purposes is typically accompanied by changes in the structure of existing samples. It is known that working processes involving the movement of ground vehicles are of an oscillation nature. It is also known that the parameters of the oscillation process depend, in particular, on the structural parameters of the running gear, road parameters, driving conditions. The parameters of the oscillating process of an object (movement, speed, acceleration) are predetermined by both the natural parameters of the

object (weight, elastic, damping, dimensional, etc.) and the perturbation parameters (base surface profile, the presence of non-holding links, etc.).

The performance indicators of a vehicle directly depend on the parameters of the oscillation process of the object. Such indicators include smooth movement indicators (ergonomics) and indicators of adhesion to the support surface. These indicators affect the average speed, stability, controllability, safety, and, in general, the ability to move along a predefined trajectory.

Purposefully designed damping is executed in the form of separate structural elements (shock absorbers). Shock

absorbers can employ viscous or dry friction (shock absorbers with viscous friction are most common). It is known from the theory and practice that, in its physical essence, dry friction, as a factor of damping, differs significantly from viscous damping by the effect on the oscillatory process. In particular, in terms of the effect on the presence (absence) of wheel detachment from the support surface, blocking the elastic suspension elements.

Modern suspension structures include those with combined damping (for example, suspensions with sheet springs and hydraulic shock absorbers). Such suspensions' friction is close to dry and, at the same time, viscous friction.

When determining the suspension parameters, there is a contradiction in the need to simultaneously meet the requirements for smooth running (ergonomics) and for adhesion to the support surface in the process of movement, especially on crossed terrain.

Resolving the contradiction is associated with the further advancement of the theory and practice of determining the rational structure and parameters of links among elements of the system «operator-machine-external environment».

Given the new design solutions involving features related to structural friction, further development of the toolset for the methodology of applied optimal design of complex technical systems [1] becomes relevant.

A new structural solution is, in particular, the original individual hydropneumatic suspension with a screw transfer mechanism proposed in [2]. A special feature of the new design is the existence of structural friction, whose force action depends on the effort in the elastic and damp suspension elements.

Obtaining an assessment of the above operational properties at the decision-making stage, in the process of designing a vehicle with a new suspension structure, requires additional research based on an adequate extended mathematical model.

Further advancement of toolset towards a comprehensive assessment in terms of ergonomics and adhesion to the support surface is a relevant task.

2. Literature review and problem statement

All the scientific literature chosen for this review is not the kind of literature that needs to be analyzed in 2021.

The results reported in work [3], based on studying, by the numerical method, the movement of an object with relaxing shock absorbers, demonstrate that the oscillations of the object are significantly different from harmonious ones. A similar situation can be predicted for a vehicle with a promising hydropneumatic suspension [2, 4]. That suggests that it is advisable to conduct a study on the assessment of the effect of structural friction in a promising hydropneumatic suspension on working processes based on the movement of the vehicle [2, 4]. The feasibility of the study also relates to the need to further expand the capabilities of a toolset for solving tasks in the process of designing new equipment. In particular, the toolset from papers [4–7], which considered, in one way or another, from the standpoint of the methodology for the applied optimal design of complex technical systems, the issues related to the theory and practice of working processes on ground transportation equipment for various purposes. The cited papers [4–7] make it possible to comprehensively assess the operational properties of vehicles (using mainly the examples of cross-country military vehicles). From work [5]: an estimation of the possibility

of sliding and overturning on a sloping hill in dynamics; from work [6]: assessing the stability of movement under the transitional and steady modes at turning; from work [4]: an assessment of braking in the absence of a suspension breakdown; from work [7]: an assessment in terms of ergonomics and crew safety.

Comprehensive assessment implies estimating the dynamics of the product quality for several parameters (indicators). In particular, such indicators as smooth running [2, 4], traffic stability under various road conditions [5, 6], ergonomics and safety, including detonation on explosive devices [7], etc.

However, no publications on an integrated approach for assessing the operational properties in terms of ergonomics and adhesion to the support surface, depending on the effect of structural friction in the prospective hydropneumatic suspension [2, 4], were found.

It should be noted that the existence of structural friction in the prospective suspension is a side effect on the way to the design of a hydropneumatic element with the ability to have certain reserves in order to solve issues related to the layout of the running gear. On the other hand, one must bear in mind that any non-elastic resistance in the suspension of different physical nature significantly affects working processes during oscillations. It is known that such resistance is purposefully induced to damp oscillations by shock absorbers of various designs, with the use of non-elastic resistance of various physical nature. The most common is the utilization of resistance by viscous (more common) or dry (less common) friction.

In general, the issues of improving the running properties of vehicles are still relevant, as evidenced by publications in recent years [8–11].

The complexity of solving the task is associated with a wide frequency range of the oscillation excitation factor, which does not make it possible to avoid resonances. A promising direction for resolving the issue is the combined application of several damping devices of different types at the same time, with adjusting each to its resonance. It is believed that the joint use of such devices could provide high vibroprotection indicators within the entire frequency range of perturbation during operation. However, this approach entails a significant complication of the suspension structure. The latest publications reported the design of suspensions with combined energy dispersion [9–11].

Another issue in solving the task is the difficulty of choosing the most rational option according to the results of research (both full-scale and estimation), especially those on the complex working processes of vehicle movement. The consequence of this situation is studying the working processes only in the suspensions of one-mass objects; a characteristic example of this approach is work [12].

The purpose of that approach is to obtain a preliminary idea about the choice of ways to be followed by solving the task in full.

This approach (simplified) has a long history, especially as regards the objects whose oscillations differ significantly from harmonious ones, in particular, in works [13–15].

3. The aim and objectives of the study

The purpose of this study is to consider an example of armored vehicles of the light weight category (vehicles whose parameters are close to BTR 70, BTR 80) in order to solve the problem regarding the «machine – operator –

environment» system based on an integrated approach. An integrated approach involves the simultaneous satisfaction of requirements for ergonomics and adhesion to the support surface within the methodology of applied optimal design of complex technical systems.

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

- to build an adequate mathematical model of the object for use in the development of a new product, in determining the structure and parameters of elastic damp links of structural elements, taking into consideration features related to structural friction;
- to conduct an estimation experiment to establish the parameters for assessing working processes (force, movement, speed, acceleration).

4. Materials and methods to study the impact of structural friction in the suspension of a vehicle on the operational indicators in terms of ergonomics and adhesion to the support surface

To solve the problem, the modes of free and forced oscillations of a vehicle have been considered. Free oscillations are considered when a vehicle rests on a flat horizontal support surface. The initial state before the solution is searched for ($t=0$) is the hung position of the vehicle. Under this state, the wheels do not come into contact with the support surface. Upon damping free oscillations, the driving mode begins with further movement over the characteristic irregularities of the support surface. The calculations were performed for movement on the crossed terrain under the most unfavorable conditions in terms of ergonomics regarding crew members and troops. Straight-line movement on the terrain with the same harmonic profile of the support surface under the wheels of both sides of the vehicle was simulated. It is accepted that large irregularities' height is 0.15 m; the length equals double the vehicle base; small irregularities' height is 0.05 m; the length equals a distance between the first and second wheels of the vehicle when moving forward. In terms of ergonomics, the smooth movement is considered good if the level of acceleration in a driver seat in the vertical direction does not exceed 3g when driving over large irregularities, and 0.5g when driving over small irregularities.

The first estimate for adhesion was based on the magnitude of the effort in contact of each wheel with the support surface. The second – based on the total contact effort of all wheels at the same time. In this case, the detachment of wheels from the base surface is registered. The detachment of controlled wheels makes it possible to obtain an assessment of the state of the vehicle's loss of controllability. The total contact effort makes it possible to obtain an assessment of the stability of the movement of the vehicle (the possibility of the skid state, etc.).

According to the theory of suspension spring, it is known that the most dangerous is the constant modes of movement at resonances, especially at high speeds.

A special feature of the hydropneumatic suspension is the dependence of its rigidity on the suspension travel value fk . The full suspension travel fk is within $fk=0...fkm$ (fkm is the maximum suspension travel). If one applies the concept of classical oscillation theory, then the number of natural (partial) oscillation frequencies is unlimited according to general coordinates at the current values of the relative movements of the wheels and body of the vehicle within $fk=0...fkm$.

Thus, one can argue about the range of motion speeds within which resonances may occur.

The estimated values of motion speeds were determined for conditional resonances according to the partial natural frequencies of oscillations in the general coordinates z and φ . Along the body of the vehicle – z (a movement of the center of gravity of the sprung part of the vehicle) and φ (the angular movements of the sprung part of the vehicle). Along the wheels – z_i (a movement of the center of gravity of each i -th wheel and the non-sprung part of its suspension, on both sides).

A mathematical model of the object of research (1) was built on the basis of the mathematical model reported in [4]. The mathematical model was expanded, in comparison with [4], for the additional structural friction forces in movable connections of the hydropneumatic spring (screw and splined).

The structural friction forces are dependent on the amount of elastic-damping efforts and structural features of the hydropneumatic element according to the schemes of suspensions (Fig. 1, 2).

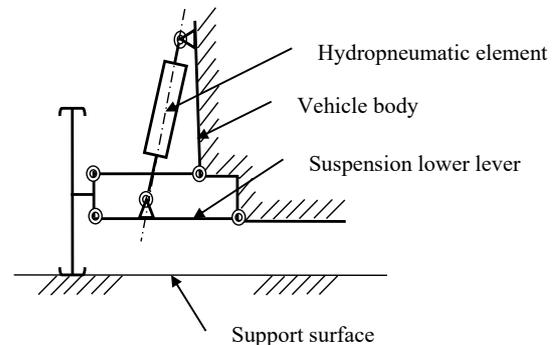


Fig. 1. Schematic showing the installation of a hydropneumatic suspension element

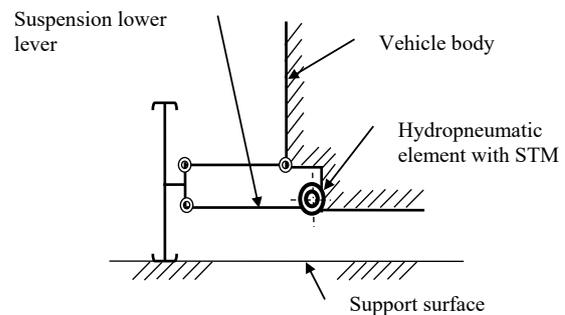


Fig. 2. Schematic showing the installation of a hydropneumatic suspension element according to variant 2 (with a screw transfer mechanism)

Structural features include the presence of a screw transfer mechanism (STM) in the hydropneumatic element (variants of STM design according to Fig. 3, 4) with a suspension scheme from Fig. 2. In particular, the STM structure (Fig. 4) includes a hydraulic cylinder connected to a lever, a piston – a nut and a screw). Movable connections in the STM structure (screw and splined) can be executed for rolling friction or sliding friction.

The theoretical study has been carried out on the basis of the original mathematical model (1) of the object of research. The model is adapted, according to the running gear design, to calculate the hydropneumatic suspension both with a traditional arrangement scheme of the hydropneumatic

element (Fig. 1) and with the new scheme (Fig. 2) of a hydropneumatic suspension with STM [7].

In line with a conventional scheme, the hydropneumatic suspension element is installed according to the scheme that is similar to the installation of a standard BTR hydraulic shock absorber (Fig. 1). According to the new scheme (Fig. 2), it is possible to implement a hydropneumatic suspension with STM either in line with a design in Fig. 3 or with a design in Fig. 4.

Regarding the non-elastic resistance in the suspension, the mathematical model according to the scheme in Fig. 1 takes into consideration the hydraulic resistance during oscillations only. According to the scheme in Fig. 2 (unlike the scheme in Fig. 1), the mathematical model takes into consideration not only the hydraulic resistance during oscillations but also non-elastic resistance due to friction forces in the screw and splined connections of STM. According to the new scheme (Fig. 2), it is possible to implement a hydropneumatic suspension with STM in line with the design in Fig. 3, or in a more compact structure in the longitudinal direction using the design in Fig. 4.

A hydropneumatic spring-lever is installed on the vehicle body at the site of the elastic element of a standard vehicle's torsion suspension. According to the design (unlike the design in Fig. 3), the hydraulic cylinder is rigidly connected to the suspension lever, and not the screw. In this case, the structure is more compact in the longitudinal direction due to the location of the screw and splined joints within the lever.

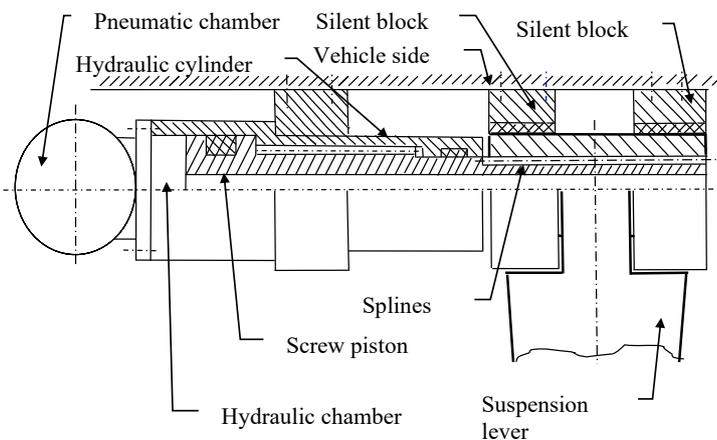


Fig. 3. Hydropneumatic suspension with a screw transfer mechanism

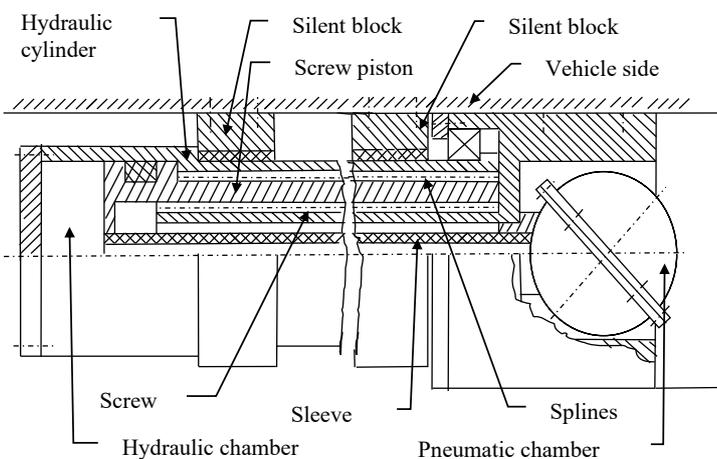


Fig. 4. Hydropneumatic spring-lever

As an example, the effect of structural friction on the indicators for ergonomics and interaction of the vehicle with the support surface was investigated. The chosen object of research is a vehicle whose structure and parameters are close to BTR70, BTR80. The object of research differs from BTR70, BTR80 only by a suspension design.

The speeds of the vehicle selected for this study are within the ranges of the estimated resonance speeds and are given in Table 1.

An estimation experiment was carried out involving two variants of suspension designs: variant 1 – according to the scheme in Fig. 1, variant 2 – according to the scheme in Fig. 2. It was accepted that the suspensions in both versions have the same elastic and damping properties brought to the wheel. This implies damping properties due to the non-elastic hydraulic resistance in the hydraulic part of the hydropneumatic suspension element. Variant 2 differs from variant 1 by the existence of structural friction PTR_{zpi} efforts, also brought to the wheels. According to mathematical model (1), at $fTR=0$ (fTR is the reduced coefficient of friction for the screw and splined joints); variant 2 does not differ from variant 1.

During calculations, values for the friction coefficients (f_{oper} – for a ball-screw joint, f_{shl} – for a splined joint) were taken from known data in the reference books, according to which the approximate values of friction coefficients for the friction pairs «steel – steel» are: the rolling friction coefficient for tempered steel is 0.001, and the slip friction coefficient, in the presence of lubrication, is within 0.005..0.1.

The estimation experiment was carried out using the Runge – Kutta method with a variable pitch and the original estimation program.

5. Results of studying the impact of structural friction on operational indicators

5.1. A mathematical model of the object of research

$$M \cdot \ddot{z} = \sum_{i=1}^4 (P_{zpi} + PTR_{zpi}) - \sum_{i=1}^4 (NP_{zpi} + NPTR_{zpi}) - G;$$

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

$$m_1 \cdot \ddot{z}_1 = Sp1k - G_1 - (P_{zp1} + PTR_{zp1});$$

$$m_2 \cdot \ddot{z}_2 = Sp2k - G_2 - (P_{zp2} + PTR_{zp2});$$

$$m_3 \cdot \ddot{z}_3 = Sp3k - G_3 - (P_{zp3} + PTR_{zp3});$$

$$m_4 \cdot \ddot{z}_4 = Sp4k - G_4 - (P_{zp4} + PTR_{zp4});$$

$$Nm_1 \cdot N\ddot{z}_1 = NSp1k - NG_1 - (NP_{zp1} + NPTR_{zp1});$$

$$Nm_2 \cdot N\ddot{z}_2 = NSp2k - NG_2 - (NP_{zp2} + NPTR_{zp2});$$

$$Nm_3 \cdot N\ddot{z}_3 = NSp3k - NG_3 - (NP_{zp3} + NPTR_{zp3});$$

$$Nm_4 \cdot N\ddot{z}_4 = NSp4k - NG_4 - (NP_{zp4} + NPTR_{zp4}), \quad (1)$$

where M , G , I_y are the mass, weight, and moment of inertia of the spring-loaded body relative to the

transverse axis OY in the coordinate system $OXYZ$ originating from O in the center of mass; $\ddot{z}; \ddot{z}_1 \dots \ddot{z}_4$ are the linear acceleration of the center of mass of the body and wheels 1–4 in the forward movement in the direction of the vertical axis OZ ; $\ddot{\alpha}$ are the angular accelerations of the vehicle body relative to the transverse axis OY ; P_{zpi} are the efforts between the wheel and body of the vehicle due to the action of the elastic and damping suspension forces; l_i is the distances in the direction of the OX axis from the center of mass of the spring-loaded body to the axle of the i -th wheel (along the vehicle); m_i, G_i is the mass and weight of the spring-unloaded suspension parts; $Sp1k, Sp2k, Sp3k, Sp4k$ are the efforts between the support surface and the wheels of the 1st, 2nd, 3rd, 4th suspensions, along the vehicle movement; PTR_{zpi} is the structural friction efforts.

A value of the structural friction effort PTR_{zpi} is calculated as a function of the value of effort P_{zpi} (an effort between the wheel and body of the vehicle due to the action of the elastic and damping suspension forces).

$$PTR_{zpi} = fTR \cdot P_{zpi} \cdot \text{sign} V_{vidn},$$

where fTR is the reduced friction coefficient for friction in the screw and splined joints; V_{vidn} is the relative speed of the wheel and body of the vehicle in the direction of the vertical axis OZ . N in the differential equations denotes the forces on the vehicle's right-hand side in the forward movement.

5. 2. Results of numerical experiment

The results of the numerical experiment are given in Tables 1–3.

Table 1

Estimated values of resonance motion speeds according to the partial frequencies of free oscillations and the lengths of irregularities

Vehicle part	Generalizing coordinate	Irregularity length, m	Resonance speed, km/h
body	z	8.8	30.363
		1.35	4.658
	φ	8.8	22.676
		1.35	3.479
wheel	z _i	8.8	65.679
		1.35	10.076

Table 2

Results of estimating the ergonomics and interaction with the support surface for variant 1 ($fTR = 0$)

Speed, km/h/irregularity length, m	Acceleration a_{VOD} in a driver seat, m/s ² (maximal amplitude)	Effort $SYSpk$ in contact with the support surface: max/min, N	Wheel detachment from the support surface	Suspension breakdown
Steady movement over large irregularities				
30.363/8.8	16.875	334,426/52,458	First and second wheels	First and fourth wheels
65.679/8.8	6.25	150,819/98,359	Absent	Absent
Steady movement over small irregularities				
4.658/1.5	1.0	141,639/108,196	Absent	Absent
10.076/1.5	2.343	134,426/104,918	Absent	Absent
32.839/1.5	4.062	233,606/18,688	On all wheels	Absent
65.679/1.5	2.343	225,409/20,491	On all wheels	Absent

Table 3

Results of estimating the ergonomics and interaction with the support surface for variant 2 ($fTR = 0.085$)

Speed, km/h/irregularity length, m	Acceleration a_{VOD} in a driver seat, m/s ² (maximal amplitude)	Effort $SYSpk$ in contact with the support surface: max/min, N	Wheel detachment from the support surface	Suspension breakdown
Steady movement over large irregularities				
30.363/8.8	18.75	367,213/32,786	First and second wheels	First and fourth wheels
65.679/8.8	7.81	153,333/95,333	Absent	Absent
Steady movement over small irregularities				
4.658/1.5	0.906	157,377/98,360	Absent	Absent
10.076/1.5	2.187	137,704/111,475	Absent	Absent
32.839/1.5	5.0	250,819/12,295	On all wheels	Absent
65.679/1.5	1.875	206,967/28,688	On all wheels	Absent

Table 1 gives the estimated values of resonance motion speeds determined by the ratio of the values of the partial frequencies of free oscillations and the lengths of irregularities. Tables 2, 3 give the results from an estimation experiment for two versions of suspension designs: variant 1 – according to the scheme in Fig. 1, variant 2 – according to the scheme in Fig. 2. As regards ergonomics, the maximum amplitudes of *aVOD* accelerations in a driver seat are given. As regards adhesion, the maximum and minimum values of the value of the total effort *SYSpk* in contact with the support surface are given. In addition, the states regarding the presence (absence) of wheel detachment from the support surface, and suspension breakdowns are given. Fig. 5, 6 show the results in the form of charts for the acceleration *aVOD*.

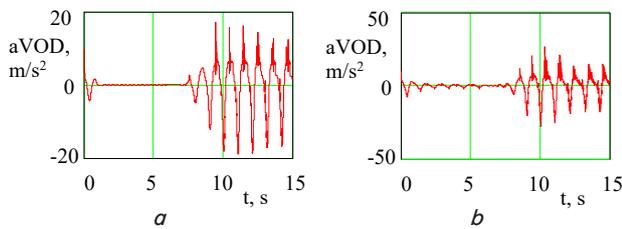


Fig. 5. Acceleration *aVOD* in a driver seat at a speed of 30.363 km/h: *a* – *fTR*=0; *b* – *fTR*=0.085

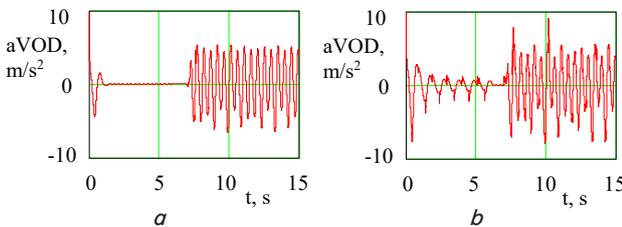


Fig. 6. Acceleration *aVOD* in a driver seat at a speed of 65.79 km/h: *a* – *fTR*=0; *b* – *fTR*=0.085

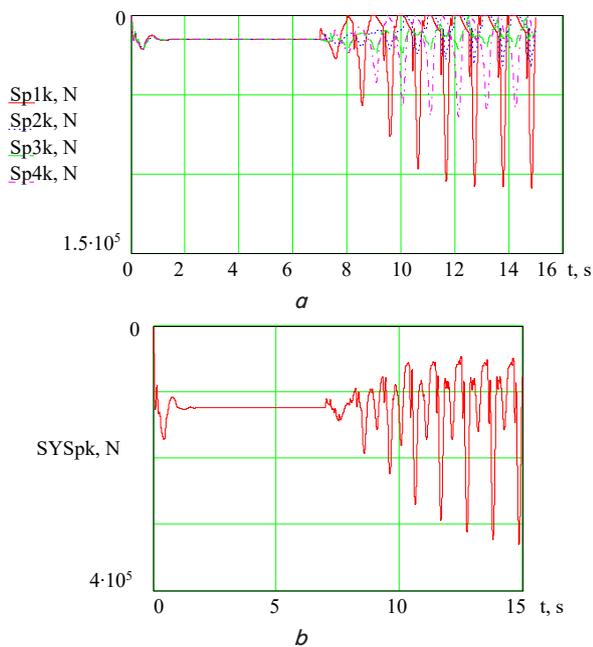


Fig. 7. Efforts in contact of wheels with the support surface at a speed of 30.363 km/h and *fTR*=0: *a* – *Sp1k*, *Sp2k*, *Sp3k*, *Sp4k* – efforts on each wheel on both sides along the course of movement (wheels 1, 2, 3, 4); *b* – *SYSpk* – total effort on all wheels at the same time

Fig. 7–10 show the results in the form of charts for the contact efforts *Sp1k*, *Sp2k*, *Sp3k*, *Sp4k* (effort on each wheel on both sides), and *SYSpk* (total effort).

The charts in Fig. 5–10 were built for variant 1 (*fTR*=0) and for variant 2 (*fTR*=0.085) for speeds of 30.363 km/h and 65.79 km/h when moving over large irregularities.

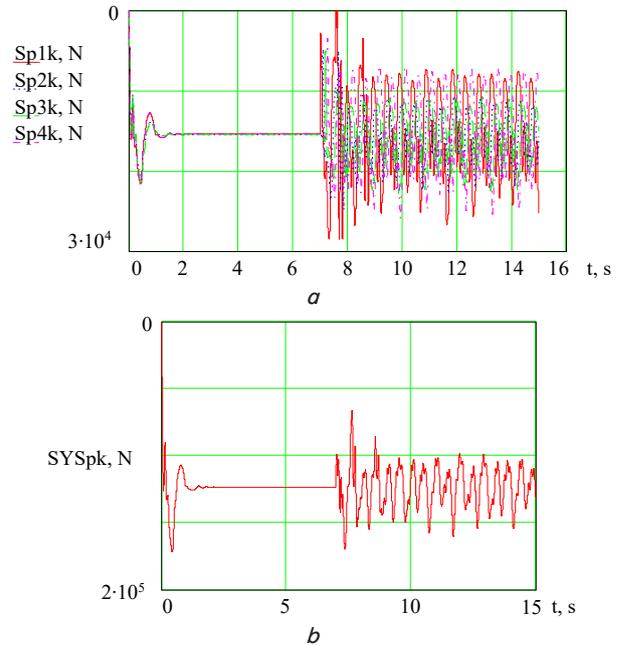


Fig. 8. Efforts in contact of wheels with the support surface at a speed of 65.79 km/h and *fTR*=0: *a* – *Sp1k*, *Sp2k*, *Sp3k*, *Sp4k* – efforts on each wheel on both sides along the course of movement (wheels 1, 2, 3, 4); *b* – *SYSpk* – total effort on all wheels at the same time

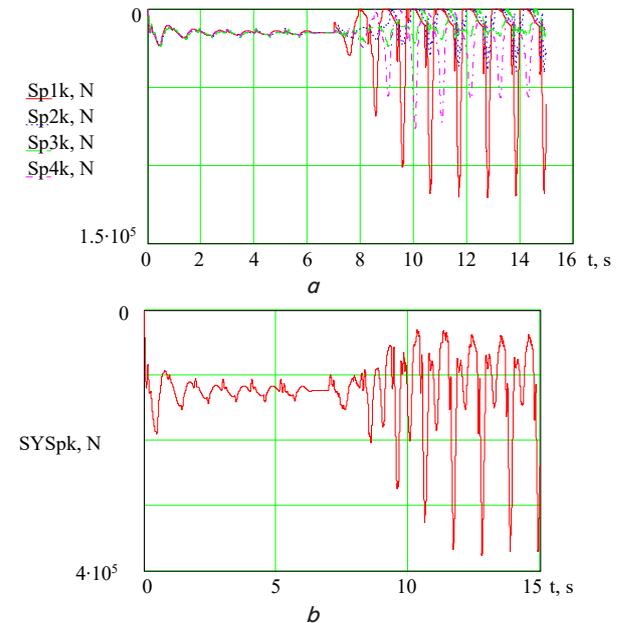


Fig. 9. Efforts in contact of wheels with the support surface at a speed of 30.363 km/h and *fTR*=0.085: *a* – *Sp1k*, *Sp2k*, *Sp3k*, *Sp4k* – efforts on each wheel on both sides along the course of movement (wheels 1, 2, 3, 4); *b* – *SYSpk* – total effort on all wheels at the same time

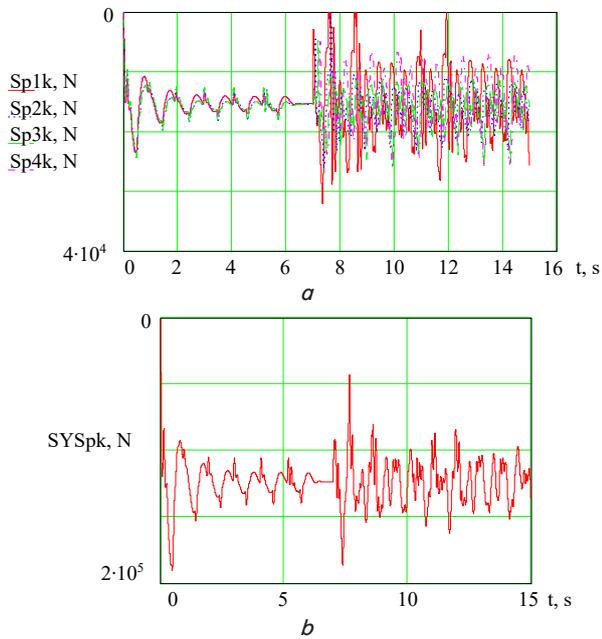


Fig. 10. Efforts in contact of wheels with the support surface at a speed of 65.79 km/h and $fTR=0.085$:
 a – $Sp1k, Sp2k, Sp3k, Sp4k$ – efforts on each wheel on both sides along the course of movement (wheels 1, 2, 3, 4);
 b – $SYSpk$ – total effort on all wheels at the same time

6. Discussion of results of studying the parameters and states of the object

The charts (Fig. 5–10) of the workflows demonstrate that the response of the study object to external perturbation differs significantly in the case of structural friction ($fTR=0.085$) from the case in its absence ($fTR=0$). The oscillation time of accelerators $aVOD$ when the vehicle rests on a flat horizontal support surface (within the time from 0 to 7 sec) at $fTR=0.085$ (Fig. 5, b, 6, b) is 4.2 times larger than at $fTR=0$ (Fig. 5, a, 6, a). A similar ratio is in the time of fluctuations in the efforts Spk and $SYSpk$ depending on the value of fTR (Fig. 7, 8 for $fTR=0$; Fig. 9, 10 for $fTR=0.085$).

The increase in the time of fluctuations in the parameters $aVOD$, Spk , and $SYSpk$ at $fTR=0.085$ in the process of free oscillations is explained by the support of oscillations by the gravity force of the spring-loaded part of the vehicle. That is, the self-oscillating properties of the object are manifested, the cause of which is the friction forces PTR_{zpi} (2) in the screw and splined movable joints in the suspension with STM (Fig. 2–4).

When hitting a surface area with irregularities (beginning on second 7), there is a transitional mode and then a conditionally steady mode of forced oscillations. The transitional stage is within 5 seconds. Starting from second 12, a conditionally steady mode is induced.

In terms of operation, forced oscillations under the steady mode of movement over a crossed terrain are of the greatest interest. The parameters of these oscillations affect the average motion speeds. Average speeds directly depend on such operational properties as smooth running, handling, stability.

In terms of ergonomics (the level of accelerations) and the stability of movement (indirectly associated with the minimum amount of effort in contact with the support surface),

the existence of structural friction may play a positive or negative role. For example, on the one hand, by reducing the acceleration (a positive aspect), and, on the other hand, by reducing the minimum amount of effort in contact with the support surface (a negative aspect). In addition, the detachment of wheels from the support surface contributes to the deterioration of controllability by the vehicle in terms of adhesion.

Tables 2, 3 make it possible to perform a comparative assessment of vehicle response to the presence (absence) of structural friction in terms of operational indicators. Based on the comparison, one can acquire information at the stage of choice between variants 1 (Fig. 1) and 2 (Fig. 2) of the structural solutions for suspensions. On the other hand, at the stage of choosing a hydropneumatic suspension with STM either based on the design in Fig. 3 or the design in Fig. 4, which is more compact in the longitudinal direction.

The adopted concept of acceleration reserve implies the number of times when the obtained value of acceleration $aVOD$ is less than permissible (3g for a large irregularity, 0.5g for a small one). The accepted concept of an adhesion reserve denotes by how many times the minimum amount of effort in contact with the support surface at $fTR>0$ is more (less) than the effort at $fTR=0$.

The vehicle speed, selected for this study, is within the ranges of the estimated resonance velocities. That refers to the range of motion speeds within which resonances can occur. The obtained ranges of the estimated resonance velocities when moving over small irregularities (a length of 1.5 m) accept the following values: along z – 4.658...9.882 km/h; along φ – 3.479...7.38 km/h; along z_i – 10.076...21.375 km/h. The corresponding ranges when moving over large irregularities (a length of 8.8 m) accept the following values: along z – 30.363... 64.414 km/h; along φ – 22.676...48.106 km/h; along z_i – 65.679...139.334 km/h. The calculations were carried out using an example of moving at the speeds (Table 1) selected from these ranges. The charts (Fig. 5–10) were built for the movement over large irregularities at speeds 30.363 km/h and 65.679 km/h. The calculations for small irregularities are limited to moving at speeds 4.658 km/h, 10.076 km/h, 32.839 km/h, 65.679 km/h; for large ones – 30.363 km/h and 65.679 km/h (Tables 2, 3).

Advancing the approach to solving the set problem, as well as similar ones, involves the further development of methodology for the applied optimal design of complex technical systems in terms of its toolset.

7. Conclusions

1. The presence (absence) of structural friction in the suspension ambiguously (positively or negatively, depending on the driving conditions) affects the smoothness of travel and adhesion to the support surface. The value of structural friction forces is predetermined by the dependence between the amount of the elastic and non-elastic (damping by hydraulic resistance) components of the effort between the wheel and body of the vehicle. The magnitude of the structural friction forces also depends on the design features and parameters of the transfer mechanism between the wheel and body of a vehicle. On the frictional properties of friction pairs (screw and splined joints) – a friction coefficient (in particular, rolling or sliding). The constructed mathematical model of the study object is adequate in response to changes in the structural friction forces under the transitional and steady motion modes.

2. The results of a theoretical study involving a vehicle whose parameters (weight, dimensions) are close to armored personnel carriers BTR70, BTR80, but equipped with hydro-pneumatic suspensions, have shown that driving in crossed terrain with speeds up to 65 km/h provides for a significant reserve in terms of ergonomics (smoothness of travel) regardless of the value of fTR (both at $fTR=0$ and at $fTR=0.085$). When driving under a steady mode at a speed of 65.679 km/h over the surface with large irregularities (the length of the irregularity is equal to the double base of the vehicle; height, 0.15 m), the reserve for the maximum allowable (3 g) accelerations in a driver seat is 4.708 times ($fTR=0$) and 3.768 times ($fTR=0.085$). At $fTR=0.085$, the reserve is smaller than at $fTR=0$.

When driving also under a steady mode at a speed of 65.679 km/h over the surface with small irregularities (the length is equal to the distance between the first and second wheels of the vehicle; height, 0.05 m), the reserve for the maximum allowable (0.5 g) accelerations in a driver seat is 2.093 times ($fTR=0$) and 2.616 times ($fTR=0.085$). At $fTR=0.085$, the margin is greater than when $fTR=0$.

Under the most dangerous modes of movement (at the highest speeds), when driving over small irregularities, the presence of structural friction ($fTR=0.085$) exerts a positive effect both in terms of ergonomics and stability. Thus, when driving at a speed of 65.679 km/h, the minimum adhesion margin is 1.4 times greater, and the acceleration is 1.249 times smaller.

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