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COMPARING THE PHYSICAL PRINCIPLES OF ACTION OF SUSPENSION DAMPING DEVICES BASED ON THEIR INFLUENCE ON THE MOBILITY OF WHEELED VEHICLES

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This paper reports the comparison of two physical principles of action of suspension damping devices based on their influence on the mobility indicators for an 8×8 wheeled machine. A radical difference between these principles of action is the dependence of resistance forces on the speed of the relative movement of working bodies (internal friction: hydraulic shock absorbers) or on the relative movement of working bodies (external friction: friction shock absorbers).

Widespread hydraulic shock absorbers have certain disadvantages that do not make it possible to further increase the mobility of wheeled or tracked vehicles without the use of control and recuperation systems. In turn, in friction shock absorbers, the use of new materials has eliminated many of their shortcomings and thus can provide significant advantages.

It was established that the application of friction shock absorbers for a given wheeled vehicle did not significantly affect the speed compared to hydraulic ones. The main factor that prevented the implementation of the advantages of friction shock absorbers was the insufficient suspension travel. However, friction shock absorbers absorbed 1.76...2.3 times less power, which reduced the load on nodes and increased efficiency (autonomy). In addition, a more uniform load on suspensions was ensured, which improved their resource, and, due to the prevailing vertical oscillations of the suspended body over the longitudinal-angular ones, the geometric passability improved as well.

The comparison of two physical principles of action of damper suspension devices in a wheeled vehicle has shown that the use of friction shock absorbers could provide significant advantages in resolving the task relates to improving the mobility and would fundamentally affect the choice of the suspension energy recuperation system if it is applied

Keywords: wheeled vehicle, mobility, suspension, damping devices, friction shock absorbers, recuperation system

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1. Introduction

Damping devices (DDs) are an important component of the suspension in a vehicle. The achieved level of both functional and economic and anthropological criteria for vehicle design, in particular mobility and its indicators, depends on DD perfection. That is why researchers in developed countries are constantly looking for new technical solutions (TSs) and the physical principles of action (PPA) of suspension nodes and new materials for their execution. This is especially true of vehicles intended for movement in cross-country areas with high average speeds, in particular military wheeled vehicles (WVs), for which mobility indicators are among the main ones.

At present, there are several PPAs of DD in a vehicle suspension. Some of them are widespread, some are only at the level of patents and prototypes, others are in the stages of research and improvement. The most widespread PPA now is based on the conversion of the energy of oscillations in a vehicle's suspended body into thermal energy by means of internal friction, which is implemented in the form of hydraulic shock absorbers (HSAs). Their feature is the dependence of resistance forces on the velocity of the relative movement of working bodies (piston or blade), that is, the speed of lifting and lowering of the wheel or roller. Much less common is PPA that is characterized by the transformation of the energy of the above-mentioned oscillations into thermal energy by means of external friction: its implementation is friction shock absorbers (FSAs). Their feature is the constant magnitude of resistance forces or their dependence on the relative movement of working bodies (friction surfaces), that is, suspension travel. All other known PPAs also implement the dependence of resistance forces either on the speed of movement (for the most part) or on the amount of movement, or on the speed and movement at the same time. These include PPAs such as the use of intermolecular resistance (elastomer DDs), pneumatic DDs, the application of smart materials, in particular magnetorheological fluids and elastomers, inertial DDs (flywheels), electric DDs (generators of various types).

Among the requirements for the suspension of modern and promising WVs, especially for military purposes, the requirements for further increase in their mobility and efficiency stand out. These issues are solved in two directions – the use of various systems for managing the characteristics of suspension units, including DDs, and the introduction of certain systems to recover the energy that is irrevocably lost in suspension DD.

However, despite a large body of scientific research and numerous patents, and given many unresolved problems, there are currently neither control systems nor recuperation systems that would be suitable for widespread implementation. This applies to WVs for both civilian and military purposes. This fact is explained by the fact that their achieved scientific and technical level contradicts the socio-economic expediency. This contradiction could be eliminated through the search, analysis, and application of new effective PPAs and TSs for suspension units, as well as control and recuperation systems, which would provide for a significant increase in technical and economic indicators at relative simplicity and low cost.

Thus, it is a relevant scientific task to analyze the PPAs of vehicle's suspension DDs, to study their impact on mobility and the related choice of PPA for the energy recuperation system in a suspension. Solving it would make it possible to devise effective TSs suitable for wide use, as well as improve the mobility and efficiency of vehicles.

2. Literature review and problem statement

The main directions of development of weapons and military equipment in Ukraine over the long term imply the supply to military units of modern samples of automotive equipment for various purposes, designed on the basis of unified vehicles with a 4×4, 6×6, 8×8-wheel formula [1]. Such WVs should demonstrate the enhanced characteristics of mobility, maneuverability, autonomy, efficiency, and protection of troops. The need to pay attention to the development of samples of automotive equipment with combined (hybrid) power plants is indicated. A separate point is to devise technology to test concepts and technical solutions without building their physical analogs and conducting their full-time tests. Thus, research in this area is relevant; a variant of the solution to the tasks set could be to use, in the WV suspension, FSAs instead of HSAs.

As part of the implementation of the GXV-T (Ground X-Vehicle Technologies) program, the DARPA Office of Advanced Defense Research (USA) has published its results on constructing a combat WV [2]. Compared to the existing ones, it has twice the speed and provides for a passability of 95 % over the crossed terrain. This vehicle is equipped with a METS (Multi-Mode Extreme Travel Suspension) suspension developed by Pratt & Miller (USA), which makes it possible to move off-road at high speed, instantly adapting to landscape changes. Its peculiarity is that under a normal suspension mode, the METS system dynamically travels over only 150 mm. When moving along a deeply crossed landscape, the suspension is transferred to a mode with a full suspension travel, which reaches 1,070 mm upwards and 760 mm downwards. Given this, WV equipped with the METS system can move over almost any surface, keeping the body in a horizontal position. That confirms the significant impact of the dynamic suspension travel on mobility indicators. However, HSAs were applied in this WV; no comparison with FSAs was considered.

The basics of design and research of a vehicle's suspension DD are presented in detail in work [3]. The structures and calculation of HSA, FSA, and pneumatic hydraulic DD, their advantages and disadvantages are considered. The technical and economic indicators of DD operation and their functional and cost analysis are given. The calculation of oscillation damping by the combined nonlinear resistance forces with construction of amplitude-frequency characteristics and choice of optimal characteristics for HSA is presented. Nevertheless, the cited study is mostly of qualitative nature, with simplified mathematical models of vehicle movement used; no real road conditions of varying severity were considered. In addition, the influence of the dependence of DD resistance forces (due to the speed or movement of working bodies) on vehicle mobility was not considered.

Paper [4] reports an analysis of the evolutionary development and the classification of well-known PPAs for suspension DD TSs used on military tracked vehicles (TVs) and WVs. Their shortcomings, causes, and contradictions of development were considered. The influence of the nature of resistance forces in the military TV suspension DD on the smoothness of its drive and the load on the chassis when moving over a low-frequency harmonic road profile was investigated. It was shown that the suspension equipped with FSA and a full travel of 420 mm, of which 300 mm account for a dynamic travel, significantly wins compared to the equivalent suspension equipped with HSA. However, only TV and its movement over one type of harmonious road profile was considered. No WV was considered, which, due to the specificity of torque supply to the drive wheels, typically has a half smaller full suspension travel than that of TV. Also, no movement of the vehicle over real road profiles with irregularities of different severity typical of rough terrain was considered.

The design of tanks' suspension, their features and characteristics were considered in work [5]. Data on the Leopard-2 tank (Germany) are given, which is equipped with FSA whose resistance depends only on the movement of the support rollers while the full travel of its suspension is 530 mm, of which the dynamic travel is 350 mm. It is indicated that the prevailing type of oscillations of the suspended body is vertical at which rollers are more evenly loaded, the useful energy of all suspension units is utilized more fully, and the engine power is used to a greater extent when driving over irregularities. In addition, these FSAs have twice as much inter-repair mileage as HSA and are not serviced during operation. Given this, as well as the use of energy-efficient hydraulic springs, the suspension of a given tank is still considered the most perfect. In turn, work [6] notes that due to the Teflon coating of the friction discs of a given FSA and their operation in oil, the coefficients of rest and the friction of movement are approximately the same. Given this, there are no significant friction forces during the transition process from statics to dynamics. However, only TV was considered, without the analysis of DD PPA. We used those data in this article when considering the possible characteristics of FSAs when applying them for WV.

The existence of two inefficient working zones of HSA in the cycle of vehicle oscillations involving the suspension was analytically proven in work [7]. The results of experimental studies for different types of suspensions have confirmed that the impact of HSA is aimed at increasing the speed and amplitude of the oscillations of the vehicle's suspended body. The presence of inefficient working zones of HSA in the cycle of oscillations requires an increase in their damping properties in these zones based on the modern methods of characteristics control. That indicates the shortcomings in a given PPA in terms of preventing the swinging of the suspended body when moving over irregularities, as well as the need for the increased energy intensity of HSA. An option to fix these problems may be the use of FSA.

Paper [8] considers four strategies for managing the resistance of friction dampers based on the analysis of the type of hysteresis loop; the authors have numerically and experimentally determined their advantages and disadvantages. It is noted that the main advantage of friction dampers is their high efficiency at low speeds of movement of working bodies. However, no studies of vehicle mobility indicators were carried out.

The truck suspension with a multi-sheet spring suspension was investigated in work [9]. It is noted that friction between the sheets of the spring has a significant impact on the parameters of smooth running. The purpose of the cited work was to determine the effect of load at an unchanging friction coefficient on the capability of the suspension to reduce the level of vibrations transmitted to the vehicle body. However, no comparison with HSA and movement under different road conditions were considered.

The dynamic properties of a many-sheet spring used in the suspension of a light commercial vehicle were considered in work [10]. The effects of friction in the spring, the frequency and amplitude of oscillations on the dynamic rigidity of the spring were evaluated. Friction was considered only in the context of the forced presence and the need to take it into consideration, without analyzing the influence of DD PPA on mobility indicators.

Work [11] investigated energy losses in the HSA of suspension in the armored personnel carrier BTR-4 when driving over ground roads of varying severity. It has been shown that starting at a speed of 20 km/h those losses increase sharply under all road conditions. The total maximum power absorbed by all suspension's HSAs, depending on the speed of movement and road conditions, was 2.1...19.5 kW, or 0.57...5.3 % of the maximum engine power. Thus, the use of a recuperation system with an average efficiency of 0.5 would make it possible to generate an amount of energy comparable to the energy of a regular generator with a rated capacity of 4.2 kW. It has been shown that the required smoothness of travel over the entire range of speeds was provided only when driving under light road conditions, and, partly, when driving under medium harsh road conditions. That indicates the insufficient dynamic suspension travel, as well as the energy intensity and efficiency of HSA used. These problems can be solved by using FSA instead of HSA. As a result of the cited research, the expediency of the design and application of a certain energy recuperation system in a suspension for the armored personnel carrier BTS-4 was substantiated.

Work [12] assesses the potential of recuperation systems of the energy absorbed by a vehicle's suspension DD; it was recognized to be large. It has been shown that the energy efficiency of such recuperation systems is on average 50 %. Various methods of recuperation were considered; the hydraulic recovery system and factors influencing its characteristics were studied in detail. It was concluded that the introduction of the energy recuperation system in traditional suspension could increase the efficiency of vehicle's energy utilization and improve its integrated characteristics. However, no attention was paid to the nature of dependence of the resistance forces of regenerative DDs. The results of the cited study were used in assessing the influence of DD PPA on the choice of the type of energy recovery system that is absorbed by them.

Paper [13] considers the potential of methods for reproducing the energy of vehicle oscillations. Based on the research, it is claimed that hydraulic and electrical recuperation systems have high productivity and development potential, and their energy reproduction efficiency reaches 60 %. That could increase fuel utilization efficiency by 2.5 %. However, the considered recuperation systems implemented the dependence of resistance forces only on the speed of the movement of working bodies. No analysis of DD PPAs and their impact on the choice of the recuperation system was carried out.

Work [14] examines the status of the problem and the analysis of designs of energy recuperation systems in WV suspensions. It is noted that up to 30 % of fuel energy is consumed for car oscillations, which is then irrevocably lost in the form of heat. The classification of recuperation systems, which are divided into electrical, hydraulic, pneumatic, and inertial mechanical, is given. Their known structural implementations were considered. The analysis of the above TSs reveals that almost all of them implement the dependence of resistance forces only on the speed of the movement of working bodies, which is characteristic of HSA. No FSA PPA was considered.

Paper [15] assesses the effectiveness of the energy recuperation system in the suspension of a car. Classifications and advanced analysis of publications on the calculation of the effectiveness of these systems and factors that affect the recuperative and damper characteristics of the suspension are given. It is shown that efficiency depends on the category of road, speed, the parameters and characteristics of suspension, the type of recuperation system, etc. However, there was no comparison of the influence of the PPAs of recuperative DDs on the mobility indicators of WV.

Work [16] defines the patterns of functioning, features in the structural execution of the components, and formulates requirements for magnetorheological elastomers (MREs) when they are used as additional DDs to manage the elastic and damping characteristics of a WV suspension. The authors designed, patented, and investigated the structures of controlled elastic hinges of suspension levers with MRE. It was established that controlling the module of losses in hinges with MREs (that is, damping properties) affects to a much greater extent the ability to improve the ride smoothness than controlling their elasticity module (that is, elastic properties). The control laws that were stated, as well as the rational values for the modules of losses and elasticity of hinges with the MRE of suspension levers, have made it possible to increase the minimum «permissible» heights of irregularities throughout the entire range of speeds and lengths of irregularities by 35...42 %. That indicates the high potential for increasing WV mobility by managing the characteristics of DD of its suspension. Nevertheless, the authors considered the dependence of DD resistance only on the speed of movement of working bodies while the potential for applying resistance dependence only on movement was not assessed.

Work [17] proposes the use of electromagnetic oscillation dampers in a vehicle suspension. The authors devised procedures for choosing the optimal parameters for an electromechanical shock absorber for the subway car, where there is no mechanical contact and friction between the components. That should increase their resource and reliability in operation. The disadvantage of a given shock absorber is a complex and expensive control system. An option for solving these problems may be the use of DD PPA.Paper [18] considers the modeling of the dynamic processes in an electromechanical shock absorber in the subway car. The dependence of resistance forces only on the speed of movement of working bodies has been implemented. Resistance dependence on movement was not considered.

Our review of the scientific literature has demonstrated that as a result of certain advantages manifested in the old days, the WM suspension continues to widely employ DD in the form of HSA, or structures with a similar dependence of resistance forces. For this reason, most systems that control their characteristics, as well as energy recuperation systems, are currently also designed with the use of certain hydraulic units where the dependence of resistance forces on the speed of movement of the wheel is implemented. On the other hand, widespread HSAs have certain disadvantages that do not make it possible to ensure further increase in vehicle mobility over the ground without any problems, and complicate the construction of simple, reliable, operational control and recuperation systems. In turn, the application of modern technologies and materials makes it possible to eliminate the deficiencies identified in the past and to design reliable and durable DD structures in the form of FSAs that could implement the dependence of resistance forces on the movement of the wheel. Nevertheless, there are almost no studies into the impact of FSAs on WV mobility and their comparison with HSAs.

3. The aim and objectives of the study

The aim of this study is to compare two suspension DD PPAs (the dependence of resistance forces on the speed of movement of the wheel: HAS; or its movement: FSA) on their impact on WV mobility and the related choice of a DD energy recuperation system.

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

– to compare the indicators of mobility and power, absorbed by DD, for WVs equipped with HSAs and WVs equipped with FSAs;

– to assess the power absorbed by HSAs and FSAs of different suspensions and compare the uniformity of their dynamic load;

– to analyze the impact of DDs PPA on the system that recuperates the energy absorbed by them, in case of its application.

4. The study materials and methods

The research was carried out using an example of a military WV with a wheel formula of 8×8, using the technique of a numerical experiment. For this purpose, we applied a multi-mass mathematical model of a military WV movement over road irregularities that we built and experimentally tested and which was implemented in the DELPHI programming environment [19]. The reliability of a given model was confirmed by comparing the estimated indicators of ride smoothness and the dynamic load on suspension units with similar indicators that were acquired experimentally as a result of polygon tests. Those tests were carried out both over real road profiles and when driving over artificial irregularities that caused the low-frequency and high-frequency oscillations of the vehicle's suspended body. The discrepancy between the calculation and the experiment was 5...15 %.

This study was carried out when a WV moved along real low-frequency road profiles of irregularities of varying severity. When constructing the speed characteristics of the suspension, we used the low-frequency harmonic profiles of irregularities that were the most unfavorable.

The WV mobility was assessed by such indicators as speed, passability, and autonomy.

In turn, the speed, among other things, is determined by the ride smoothness (the level of meeting ergonomic requirements) when driving over the most unfavorable road profiles and at average motion speed under real road conditions of the terrain. These indicators characterize the possibility of implementing the full power of the power plant, which should not be limited by imperfect suspension. The passability is divided into support-clutching and geometric. The latter, among other things, is limited to the level of oscillations of the suspended body when the imperfection of the suspension and, in particular, its DD, when moving over irregularities, leads to the suspended body hitting the ground, which reduces the speed of movement.

Autonomy is the ability to move without additional means, namely fuel stations, repair and evacuation machines, etc. It is characterized by a mileage reserve (specific fuel consumption and the amount of fuel on board), the resource of nodes, and the frequency of their maintenance. The impact factors of the suspension that limit autonomy are the large losses in DD, which, depending on the type of suspension and modes of movement, could be up to 30 % of the engine power [4, 11, 14]. That leads to poor fuel efficiency, reduces the running reserve, and, accordingly, reduces autonomy.

In addition, the suspension units are the most loaded nodes of a vehicle. Their resource, reliability, and repairability could significantly affect autonomy. Therefore, in order to improve autonomy, there is a tendency to ensure the resource of suspension units in military vehicles without replacing them until an overhaul, which must be taken into consideration when designing prospective suspensions.

Ride smoothness was determined by the level of vertical accelerations that occurred where people are seated and which should not exceed the permissible values in terms of ergonomic requirements. For military vehicles, this is 3 *g* when driving over a low-frequency road profile of irregularities.

The assessment of ride smoothness and its impact on the average speed of movement was carried out by building the speed characteristics of the suspension. They represented the dependence of the «passable» height of irregularities (the height that the suspension can overcome with accelerations in the center of masses (c. of m.) or in a driver's seat less than 3 *g*) on the vehicle speed. These characteristics were built for the case of movement over a harmonious profile with a distance between irregularities of 2 *L* (where *L* is the vehicle base), which is considered the most unfavorable, as well as at distances equal to 1.5 *L* and 2.5 *L*. The minimum values of «passable» heights of roughness which corresponded to resonant modes of movement when natural frequencies of oscillations of the suspended body coincided with the frequency of the forced fluctuations caused by road roughness were estimated. The higher the minimum «passable» height of irregularities, the better the ride smoothness and the greater the possible average speed on the ground.

Three road profiles were used as real low-frequency road profiles of irregularities, which were areas of unpaved roads and rough terrain at a test site (Fig. 1).

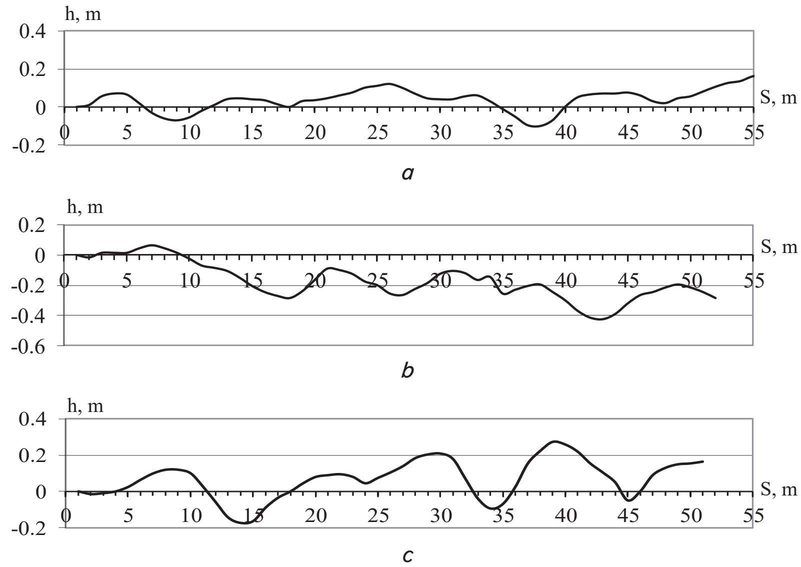


Fig. 1. Sections of the real low-frequency road profiles of irregularities: *a* — light road conditions; *b* — road conditions of medium severity; *c* — difficult road conditions

The heights of the irregularities of these profiles were measured per each meter using an optical leveler. The severity of road conditions was assessed by the integrated indicator of the intensity of road impact I_δ, which was determined from a formula given in [20]:

$$I_\delta = \frac{\pi H^2}{4L^*},$$

where H and L^* are, respectively, the arithmetic means of the height and length of irregularities. The values of the indicator I_δ for these areas were 1,030 mm^2·m^{-1}, 2,580 mm^2·m^{-1}, and 3,980 mm^2·m^{-1}, which corresponded to light, medium harsh, and difficult road conditions.

In order to exclude the influence of the suspension kinematics, a single chassis with a torsion suspension on transverse levers was considered, equipped with telescopic DDs. Two types of their characteristics were studied. In the first case, the DD had the characteristics of regular HSAs and implemented the dependence of the effort on the rod P_{rod} n the speed V_{rod} of a given rod (Fig. 2, *a*). In the second case, the DDs had the characteristics of FSAs and implemented the dependence of the effort on the rod P_{rod} on its movement h_{rod} (Fig. 2, *b*, *c*).

The above FSA characteristics are the most characteristic and were accepted taking into consideration the data from papers [4–6]. The magnitude of the maximum FSA resistance force to maintain the same working conditions was chosen close to the maximum HAS resistance force. At the same time, there was no wheel hanging and wheel separation from the soil on the reverse travel of the suspension as a result of DD operation. That is, the moment of a given effort relative to the axis of the torsion, taking into consideration the reactions in the hinges of the suspension, was less than the moment generated by the torsion itself.

The study was carried out in the range of speeds of 5.56...17.78 m/s (20...64 km/h). The maximum vertical accelerations were calculated in the c. of m. and in a driver's seat, as well as the power absorbed by the DD of different suspensions; the speed characteristics of the suspension for the characteristic lengths of irregularities were then built. These parameters sufficiently enough characterize the main indicators of mobility.

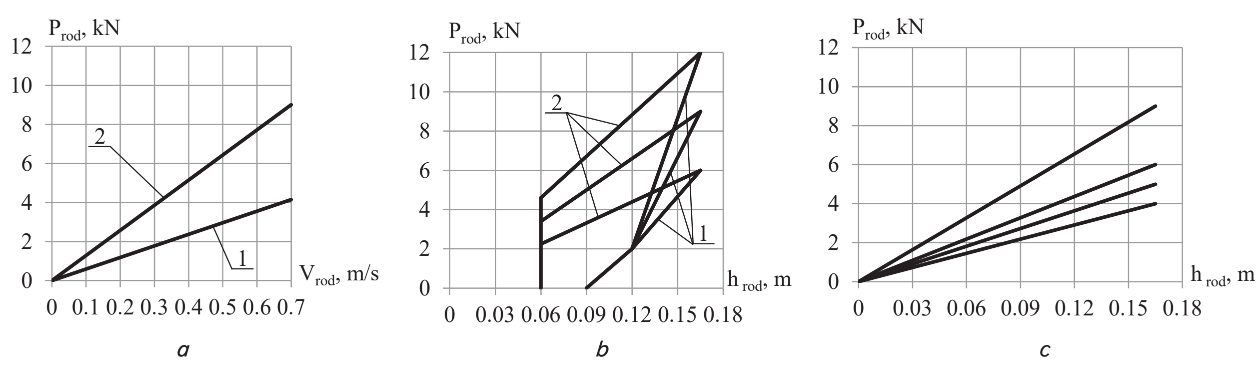


Fig. 2. Variants of characteristics for damping devices: *a* — hydraulic shock absorbers; *b* — friction shock absorbers; *c* — friction shock absorbers; 1 — forward movement; 2 — reverse movement

5. The results of studying the mobility indicators of a wheeled vehicle equipped with damping devices operated on different physical principles of action

5. 1. Comparing the indicators of mobility and power absorbed by damping devices

In the first case, we considered a variant where the WV equipped with HSA had characteristics in accordance with Fig. 2, *a*, and the WV equipped with FSA – according to Fig. 2, *b*. A given type of FSA has no resistance during the static travel of the suspension, and its characteristics differ during the forward and reverse moves and accept different values for a maximum resistance when implementing a full suspension travel.

Fig. 3 shows the speed characteristics of the suspension, comparing which reveals that the difference in the DD PPA for a given WV did not significantly affect the value of the «passable» heights of irregularities. Under the pre-resonant and resonant modes, the ride smoothness slightly improved; under the above-resonance modes – somewhat deteriorated.

The calculations showed that even a significant change in the maximum FSA resistance at the end of the dynamic travel exerted a sufficient influence only under the above-resonance modes. These are speeds exceeding 6.5 m/s, 9.0 m/s, and 11.0 m/s, respectively, for the lengths of irregularities of 1.5 *L*, 2.0 *L*, and 2.5 *L*.

Fig. 4, 5 show the vertical accelerations in the c. of m. and in a driver's seat, as well as the power absorbed by the DD of suspension *I*, which is the most loaded. The movement took place over the real profiles of irregularities that corresponded to light and medium harsh road conditions.

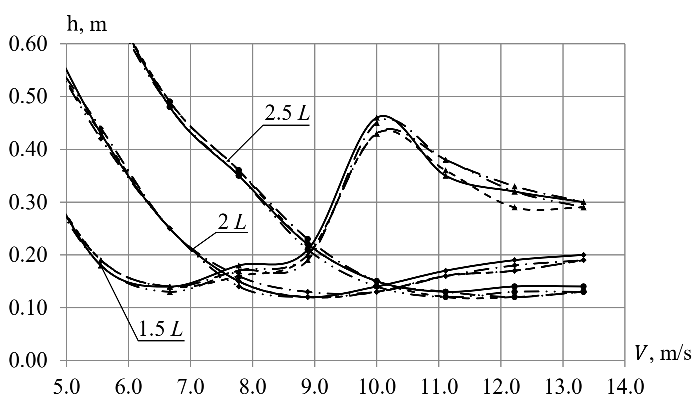


Fig. 3. Suspension speed characteristics: ——— — suspension with hydraulic shock absorbers; suspension with friction shock absorbers: —··— — $P_{rod\,\max}$=6 kN; ---- — $P_{rod\,\max}$=9 kN; -·-·- — $P_{rod\,\max}$=12 kN

The above charts demonstrate that under light road conditions, when using FSA, the ride smoothness under a pre-resonant mode (speed up to 9.0 m/s) has improved. In turn, under the resonant and above-resonant modes of movement (speed greater than 9.0 m/s), it deteriorated.

With an increase in the speed of movement, the level of vertical accelerations in a driver's seat increased by a maximum of 12 % (the FSA characteristics correspond to the smallest value of $P_{rod\,\max}$=6 kN). However, at the same time, the power absorbed by the FSA of suspension *I* decreased by 43 %, or by 1.76 times, that is, much more than the ride smoothness deteriorated.

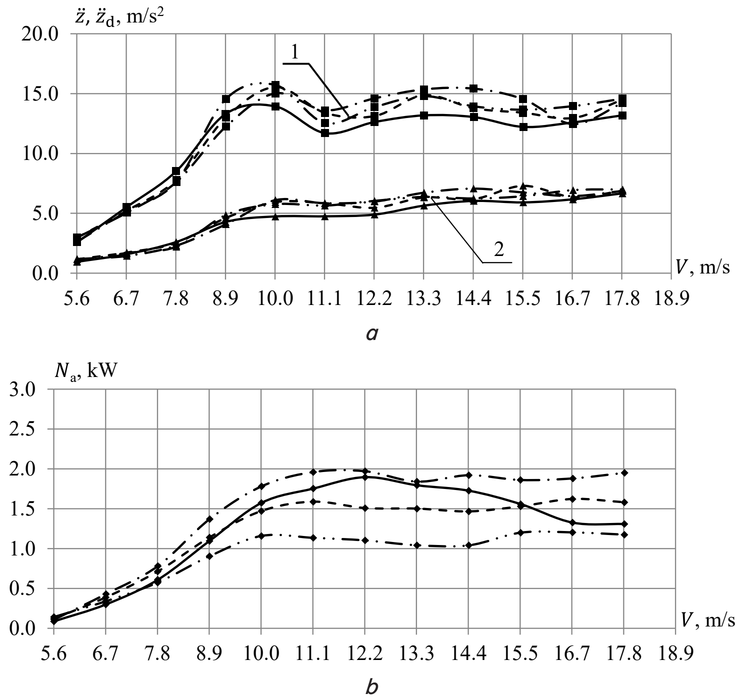


Fig. 4. Effect of the physical principle of action of damping devices on the vertical accelerations and absorbed power under light road conditions: *a* — vertical accelerations: 1 — in a driver's seat; 2 — in the c. of m.; *b* — power absorbed by damping devices of suspension I: ——— — suspension with hydraulic shock absorbers; suspension with friction shock absorbers: —··— — $P_{rod\,\max}$=6 kN; ---- — $P_{rod\,\max}$=9 kN; -·-·- — $P_{rod\,\max}$=12 kN

Under road conditions of medium severity, when using FSA, the ride smoothness under a pre-resonance mode (speed up to 7.0 m/s) remained unchanged, and, under the resonant and above-resonant modes of movement (speed greater than 7.0 m/s), also deteriorated.

With an increase in the speed of movement, the level of the vertical accelerations in a driver's seat increased by a maximum of 22 % (the FSA characteristics correspond to the smallest value of $P_{rod\,\max}$=6 kN). However, at the same time, the power absorbed by the FSA of suspension I decreased by 57 %, or by 2.3 times, that is, also much more than the ride smoothness deteriorated.

Our calculation of mobility indicators when driving over a road profile that corresponded to difficult road conditions showed that the movement of a given WV with permissible vertical accelerations was possible only at speeds of up to 5.55 m/s.

With an increase in speed, constant suspension breakdowns and a sharp increase in the vertical accelerations in people's locations were observed, which made further movement impossible.

That concerned both the suspension equipped with HSA and that equipped with FSA.

In order to study the possibility of improving mobility indicators by increasing the resistance forces of DD and choosing the rational reduced suspension rigidity, we performed appropriate calculations.

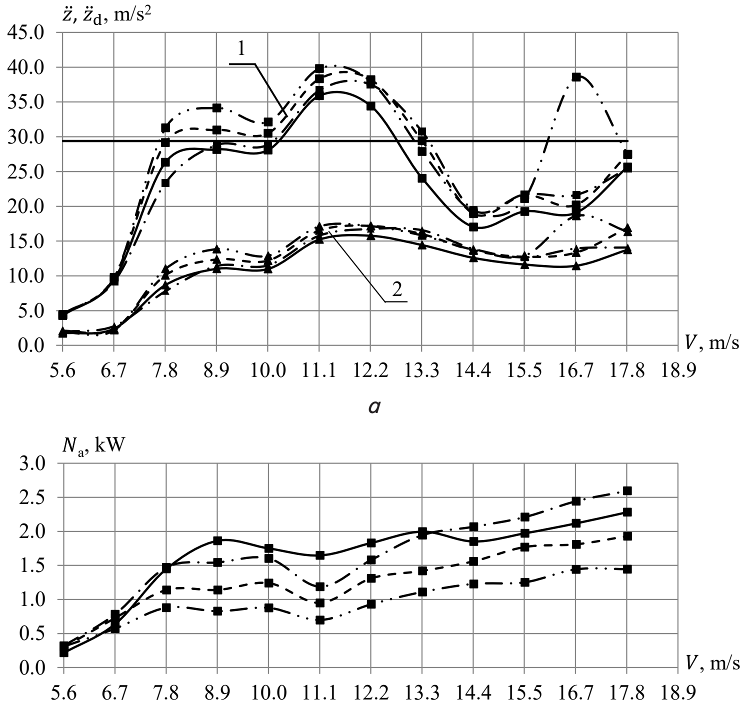


Fig. 5. Influence of the physical principle of action of damping devices on the vertical accelerations and absorbed power under road conditions of medium severity: *a* — vertical accelerations: 1 — in a driver's seat; 2 — in the c. of m.; *b* — power absorbed by damping devices of suspension I: ——— — suspension with hydraulic shock absorbers; suspension with friction shock absorbers: — · · — — $P_{rod\,\max}$=6 kN; - - - - — $P_{rod\,\max}$=9 kN; - · - · - — $P_{rod\,\max}$=12 kN

However, no positive result was obtained either in the case of HAS or in the case of FSA. Our studies have shown that the main factors that influenced the mobility indicators for a given WV were not the magnitude of DD resistance and its nature, nor the reduced rigidity of the suspension. First of all, the possibility of increasing mobility indicators was limited by a short suspension travel, both full and dynamic, which were, respectively, 220 mm and 133 mm, and were insufficient for the movement of the vehicle at high speeds under these road conditions. It should be noted that the structural features of the chassis, transmission, and body of a given WV make it difficult to increase the dynamic suspension travel to an acceptable value, without significant retrofitting.

Our results correlate with the results obtained for TV, reported in paper [4]. However, for TV, the use of FSA provided more significant advantages compared to HSA. In particular, the passable heights of irregularities at pre-resonant and resonant motion speeds increased significantly, with their permissible decrease at above-resonant speeds. The minimum «passable» height of irregularities over the entire range of speeds increased from 230 mm to 260 mm, that is, by 13 %. This is a very significant result because increasing this height even by 10 mm usually requires a significant, by tens of percent, increase in DD capacity. At the same time, the power absorbed by the DD of suspension I decreased by up to 1.7 times. Such results are explained by the fact that the TV under study had a full suspension travel at the level of 420 mm, of which 300 mm were dynamic. This is what has made it possible to implement the FSA advantages mentioned above.

In the second case, we considered an option where FSAs had characteristics in accordance with Fig. 2, *c*. These characteristics ensured an increase in resistance, starting with the hung suspension position, they did not differ during the forward and reverse moves, and accepted a different value of maximum resistance when implementing the full suspension travel. Fig. 6 shows the speed characteristics of the suspension, comparing which reveals that the suspension equipped with FSA improved the ride smoothness at pre-resonant and resonant speeds and mainly worsened it at above-resonant speeds. Moreover, the best option was the characteristic of the FSA with maximum force $P_{rod\,\max}$=6 kN when the «passable» height of irregularities under resonant modes increased by an average of 9 %.

Fig. 7 shows the dependence of the vertical accelerations and power absorbed by DD on the speed of movement, when driving WV under light road conditions.

It follows from the charts above that under an above-resonance mode the suspension equipped with FSA ensured a decrease in the vertical accelerations in a driver's seat by up to 18 % at $P_{rod\,\max}$=6 kN and up to 48 % at $P_{rod\,\max}$=9 kN (movement speed is 8.88 m/s). At the same time, the absorbed power increased by 23 % and 44 %, respectively. Under the resonant and above-resonance modes, there was an increase in the level of vertical accelerations, especially in a driver's seat, despite the increase in the power absorbed by FSA.

This is due to their too large resistance along a forward move when driving under light road conditions, which led to great forces of perturbation when hitting an irregularity. Thus, similar to the use of HSA, the resistance along the forward move of FSA should be 2...3 times less than the resistance on the reverse move, even though it depends only on the suspension travel.

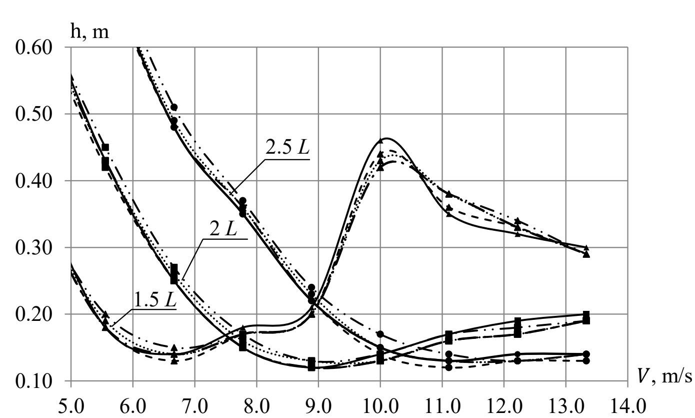
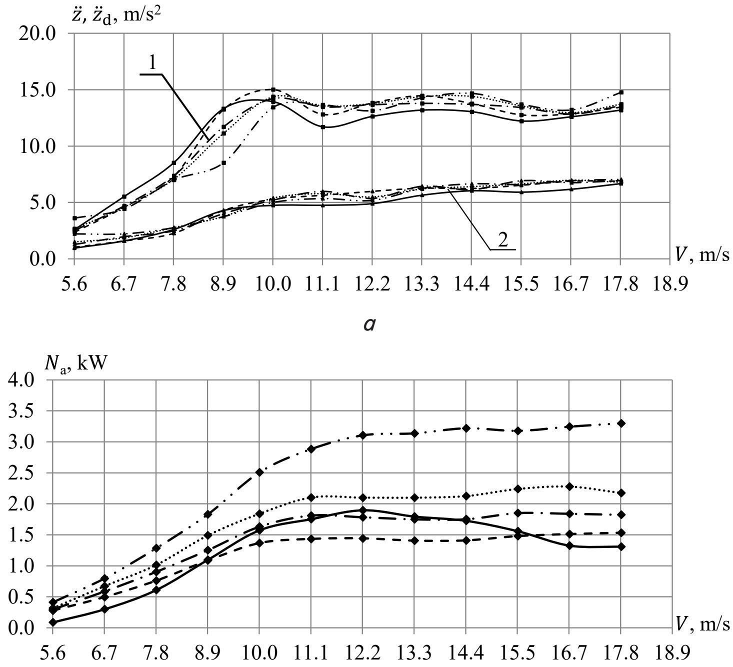


Fig. 6. Suspension speed characteristics: ——— — suspension with hydraulic shock absorbers; suspension with friction shock absorbers: - - - - — $P_{rod\,\max}$=4 kN; - · - · — $P_{rod\,\max}$=5 kN; — · · — — $P_{rod\,\max}$=6 kN; ·········· — $P_{rod\,\max}$=9 kN



a

b

Fig. 7. Influence of the physical principle of action of damping devices on the vertical accelerations and power absorbed by the damping devices of suspension I under light road conditions: *a* — vertical accelerations, 1 — in a driver's seat; 2 — in the c. of m.; *b* — power absorbed by the damping devices of suspension I: ——— — suspension with hydraulic shock absorbers; suspension with friction shock absorbers: - - - - — $P_{rod\max}=4$ kN; -·-·- — $P_{rod\max}=5$ kN; —··—— $P_{rod\max}=6$ kN; ·········· — $P_{rod\max}=9$ kN

5. 2. Evaluating the power absorbed by damping devices in different suspensions

A given assessment would make it possible to assess the uniformity of their dynamic load. Consider the movement of WV under the road conditions of medium severity.

Fig. 8 shows the dependence of the power absorbed by suspensions' DDs on the speed of movement (the FSA characteristics correspond to Fig. 2, *c*).

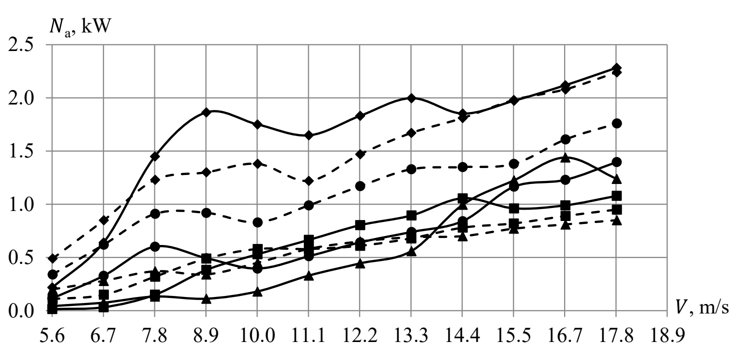


Fig. 8. Power absorbed by the damping devices of different suspensions under the road conditions of medium severity: ——— — hydraulic shock absorbers; - - - - — friction shock absorbers, at $P_{rod\max}=5$ kN; —♦— — suspension I; —■— — suspension II; —▲— — suspension III; —●— — suspension IV

It follows from the charts that the load on suspensions in the case of using FSA is much more uniform than when using HSA. This is due to the prevailing vertical oscillations of the suspended body over the longitudinal-angular ones and by the reduction of the latter.

Under the resonance motion mode (the natural oscillations of the suspended body coincide with the frequency of disturbance due to irregularities; the speed is 8.88 m/s), the HAS power of suspensions I and IV, respectively, was equal to 1.85 kW and 0.5 kW. The gap was 1.35 kW, or 3.7 times. With the use of FSA, a given indicator decreased by 1.46 times, while the power absorbed by the FSA of suspension I decreased to 1.3 kW, and the power of the FSA of suspension iV increased to 0.89 kW. The same trend was observed for most of the range of speeds of pre-resonant and above-resonance motion modes. This fact would make it possible, first, to increase the autonomy of WV equipped with FSA by reducing the load and increasing the resource of suspension units and the frequency of their maintenance. Second, it could improve the geometrical passability of the vehicle by reducing the amplitudes of longitudinal-angular and prevailing vertical oscillations, and, accordingly, would reduce the likelihood of impacts by the suspended body against the ground.

5. 3. Analyzing the influence of the physical principles of action of damping devices on the choice of type of a recuperation system

Our analysis has revealed that the using a certain DDA of DDs, which were considered, would significantly affect the TS for a DD energy recuperation system in case of its application. At the same time, there would occur a series of issues related to the following:

– the vast majority of known DDAs and TSs for recuperation systems, similarly to HSA, ensure the resistance when converting energy, which depends precisely on the speed of movement of working bodies, rather than the magnitude of their movement, which is characteristic of FSA. This applies to both electrical and hydraulic, as well as pneumatic and inertial-mechanical types of recuperation systems. Ensuring the dependence of resistance during recuperation on the movement of working bodies in known designs would certainly cause their even more complexity and reduce the expediency of their use. To resolve this issue, it is necessary to introduce the search for fundamentally new DDAs and TSs, including based on the use of new materials;

– the characteristics of a recuperation system should first of all provide for the necessary mobility indicators of a vehicle, that is, have optimal characteristics of the resistance of the recuperative DD along the forward and reverse moves of the suspension. This is mistakenly not taken into consideration by most designers.

Only after meeting these conditions, it would be necessary to ensure the rational recuperation indicators.

The issue of combining these two contradictory factors has been little investigated.

The above reported study into the power absorbed by DDs (Fig. 4, 5, 7, 8) has shown that the use of recuperation systems is effective when driving around the area at high speeds when large suspension moves occur. Their application is promising, for example, for military vehicles that are operated under appropriate conditions.

In turn, under the light road conditions and at small speeds, the efficiency of such recuperation systems drops by many times and their use, given existing shortcomings, is not yet appropriate.

6. Discussion of the research results and the possible use of friction shock absorbers in order to improve the mobility of wheeled vehicles

Our study had made it possible to identify and justify a series of advantages regarding the use of FSA, compared to HSA, in solving the task of improving the mobility of WV. This applies to indicators such as autonomy (fuel efficiency, mileage reserve, resource, frequency of maintenance) and geometric passability, which were evaluated qualitatively.

While maintaining or at a relatively minor deterioration of vehicle ride smoothness, FSAs, compared to HSAs, absorbed much less power, by 1.76...2.3 times (Fig. 4, 5).

At the same time, the level of vertical accelerations increased only by 12...22 %, that is, much less (Fig. 4, 5).

This is explained by the fact that the dependence of DD resistance on the movement of working bodies, unlike the dependence on the speed of movement, does not contribute to the swing of the suspended body exposed to the kinematic disturbance on the part of the road profile. Thus, to damp these oscillations, less DD resistance is required, which is one of the main advantages of FSA. That would improve the efficiency of the vehicle, and, accordingly, the mileage reserve and autonomy because, in the end, the suspension's DD converts into heat the energy generated by the power unit. In addition, our results confirm the well-known conclusion that another of the advantages of FSAs is their effectiveness at the low speeds of movement of working bodies (pre-resonance mode).

In addition, FSA, compared to HSA, provided a much more uniform workload on extreme suspensions, which would increase their resource and reliability. Under the road conditions of medium severity, under a resonant mode (Fig. 8; speed, 8.88 m/s), the difference between the power absorbed by the HSA of suspensions I and IV was 3.7 times. When using FSA, this indicator decreased by up to 1.46 times (Fig. 8).

In addition, due to the prevailing of vertical oscillations of the suspended body over the longitudinal-angular ones, the geometric passability of the vehicle would increase too.

Reducing the power absorbed by DD would lead to less load on suspension units, improve efficiency, and increase the frequency of suspension maintenance. This is evidenced by data on the Leopard-2 tank (Germany), whose FSAs, compared to the Leopard-1 (Germany) tank's HSAs, have twice as much resource and are not serviced during operation [5, 6].

However, the use of FSA, for the WV under consideration, did not lead to an improvement in mobility indicators such as smooth running and average speed. Under the pre-resonant and resonant modes of movement, the ride smoothness slightly improved, and, under the above-resonance modes, somewhat deteriorated. When driving in real light road conditions and under the conditions of medium severity, the ride smoothness also insignificantly improved or remained unchanged, and, under the resonant and above-resonance modes of movement, it somewhat deteriorated. That is due to the insufficient full and dynamic suspension travel in a given WV, which, respectively, were 220 mm and 130 mm, which is the main factor that prevented the implementation of FSA advantages. It is needed to significantly, up to 2 times, increase the full and dynamic suspension travel to the level of modern military TVs, respectively, 450...500 mm and 300...350 mm.

However, for a given WV, given the characteristics of its body, suspension, and transmission, there would be a need for significant retrofitting. These requirements should be taken into consideration when designing new samples of wheeled equipment. That would also correspond to the general global trends in its development.

In turn, the use of a certain DD PPA (HSA or FSA) would fundamentally affect the choice of the recuperation system in case of its application. Our analysis has shown that the functioning of most known types of systems that recuperate energy absorbed by the suspension's DDs is associated with the speed of movement of working bodies, and not with the movement itself. Therefore, when using FSA as a suspension's DD, it would be necessary to search for fundamentally new DDAs and TSs for the implementation of these systems. That could lead to some difficulties. Nevertheless, the search and research in this area may make it possible to solve the above-mentioned contradiction between the achieved scientific and technical level and the socio-economic feasibility of using known systems of DD energy recuperation. This would make the use of these recovery systems effective in most classes of vehicles.

The results reported here continue our research into the use of FSAs on military TVs where an increase in mobility indicators was obtained under almost all modes of movement [4]. They could be used in the design of new models of vehicles that are subject to the requirements for ensuring increased mobility when driving in a crossed area.

7. Conclusions

1. The use of FSA instead of HSA, in the case of a sufficient amount of suspension travel, would provide significant advantages in solving the task of increasing WV mobility. This applies to both smooth running and average movement speed, as well as geometric maneuverability and autonomy. FSAs absorbed 1.76...2.3 times less power, which would improve efficiency, reduce load, and increase the service life of chassis units.

2. The use of FSA, compared to HSA, provided a much more uniform load on extreme suspensions. The difference between the power absorbed by DDs of suspensions I and IV decreased from 3.7 times for HSA to 1.46 times for FSA, which would increase the resource and reliability of suspension units.

3. The implementation of FSA characteristics would make it impossible to use most known types of DD energy recuperation systems, or could significantly complicate their already complex design. A solution to this issue is the search for fundamentally new DDAs and TSs for such systems, as well as materials for their execution.

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