Analysis of the current state of research in the field of improving the smooth ride of vehicles equipped with suspension

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Abstract. In the article the analysis of a modern condition of research in the field of increase of smoothness of a course of various modern motor vehicles, including machines of special and military appointment is resulted. The reasons limiting the decision of a global problem of the further development of automatic telephone exchanges and growth of productivity and safety of work at performance of transport works are formulated. The basic ways of the decision of the given problem, consisting in application of regulation of characteristics of a suspension depending on driving conditions and character of fluctuations of a motor vehicle are analyzed. At the same time, it is proposed to develop fundamentally new innovative structures and algorithms to regulate the characteristics of the suspension, improving the smoothness of the ride and other operational properties of the motor vehicle.

1. Introduction

At present, the requirements to the operational properties of various modern motor vehicles are growing rapidly. This is especially true for special-purpose and military vehicles, which often have to move at high speeds on uneven roads and terrain and do not tire people with transport vibration to perform their tasks. The dump trucks have to limit their travel speed because of the intense body vibrations and the risk of overheating the tyres. «Difficult» road conditions cause up to 30% of engine power to be lost in the suspension of fast-tracked vehicles. The additional suspension of cabins and seats does not solve the problem of significant reduction of vibrations and increase of average speeds. For modern high-speed cars there is a problem of reducing the controllability, stability and braking properties on uneven roads due to the occurrence of large fluctuations and the separation of the wheels from the road, which reduces the active safety and leads to an increase in accidents.

These combined hold back the solution to the global problem of further development of motor vehicles and increased productivity and safety of transport operations, which leads to significant annual economic losses for the country, as well as affects the speed of special and military vehicles.

2. Potential solutions to the problem of smooth ride of suspension machines

One of the ways to solve this problem is to apply the regulation of suspension characteristics depending on traffic conditions and the nature of vehicle oscillations. However, the active suspension
management systems used, for example, in some high-end luxury passenger vehicles do not always provide the required increase in average speed, but significantly increase their cost. Also, the regulation of shock absorbers on new models of special equipment, although it solves the problem of increasing the speed of movement, but leads to rapid overheating of the suspensions and reduce the efficiency of their operation. The latter is due to the fact that due to the phase shift of oscillations of the vehicle frame relative to the profile of the road in the cycle of oscillations, there are zones in which the shock absorber force coincides with the direction of movement of the suspended mass, i.e. on this course the shock absorber does not brake, but, on the contrary, pushes the frame, heating up itself uselessly [1, 2].

Therefore, new suspension structures with damping controls are needed to reduce these inefficient zones, or other types of shock absorbers that operate on new principles. In this case, in order to simplify the adjustable suspension, increase their reliability and reduce costs, it is extremely important to develop, first of all, self-regulating autonomous suspension systems that do not require external control and supply of energy and have small size and weight, as well as implementing new algorithms to regulate the characteristics of the minor modernization of serial pneumatic and pneumatic-hydraulic springs and hydraulic shock absorbers [3–6].

Therefore, the task of developing fundamentally new innovative structures and algorithms to regulate the characteristics of suspensions that improve the smoothness and stability of movement, fuel efficiency, controllability and braking properties of vehicles is relevant.

3. Analysis of the current state of research in the field of smooth ride of vehicles equipped with suspension

The feature of the kinematic disturbance of the vehicle's vibrations is the phase shifts between the vertical movements of the contact point of each wheel with the supporting surface and the unsprung mass, as well as between the vertical movements of unsprung and sprung mass. The last phase shift in the oscillation cycle results in the formation of two areas where the force of the shock absorber is directed towards the movement of the suspended mass, which increases its kinetic energy and contributes to increasing the amplitudes of its oscillations. Therefore, the operation of the shock absorber in these areas is ineffective in terms of reducing the amplitudes of vibrations of the suspended mass. The beginning of each inefficient shock absorber section coincides with the stop of the suspended mass in the upper or lower position, and the end of the section coincides with the stop of the rod in the shock absorber in the upper or lower position, i.e. at the moment of changing the direction of shock absorber deformation [1]. The shock absorber is switched off or the damping level of the shock absorber is reduced by means of regulation of the shock absorber when the zones of inefficient operation are passed in each cycle of vibration, which will lead to an increase in the efficiency of the shock absorber operation and a decrease in the amplitudes of vibrations of the absorbed mass [2].

3.1. Regulation of damping in the suspension

The first works on the possibility of regulating damping in the vibration cycle appeared in the 60s of the twentieth century. Thus, in his 1965 PhD thesis "Study of some issues of damping of car oscillations" [7] the employee of the Research Institute of Construction and Architecture of the BSSR State Construction and Architecture R.I. Furunzhiev, using the principle of maximum L.S. Pontryagin[8] has shown by the example of a two-mass model of a vehicle that the optimal regulation of damping is to switch it off immediately at those parts of the vibration cycle when the direction of motion of the suspended and unsprung masses coincide, and the absolute speed of the unsprung mass is greater than the absolute speed of the suspended mass in the vertical direction, with subsequent instantaneous inclusion when these conditions change to the opposite.

R.I. Furunzhiev also noted that the elastic damping characteristic of the suspension at such regulation (force dependence on its deformation) has the form of a "butterfly".

The first references in the European and American literature to the possibility of regulating damping in the vibration cycle date back to the first half of the 1970s. The algorithm of regulation
similar to that of R.I. Furunzhiev was proposed as an alternative to expensive, very complex and energy-intensive active suspensions by American scientists D. Karnopp (D.S. Karnopp) and Crosby (M.J. Crosby) in "The Active Damper - a New Concept for Shock and Vibration Control" (1973) [9] and "Vibration Control Using Semi-Active Force Generations" (written in collaboration with R. Harwood in 1974) [10]. The suspension with this principle of damping regulation is called semi-active suspensions.

D. Karnapp also proposed another concept - a smooth change of damping in order to bring the action of the standard shock absorber closer to the action of the imaginary shock absorber, located between the suspended mass and a certain point stationary in the vertical direction (the concept of "skyhook").

Further studies of these damping control principles have revealed their significant disadvantages [11]. The first disadvantage related to the skyhook concept is the difficulty of enforcing the law of smooth damping, which is associated in English literature with the difficulty of determining the vertical velocity of the suspended mass. This disadvantage can be eliminated by introducing a constant value of the effective damping factor, thus moving to the algorithm "semi-active control suspension".

The second disadvantage is the discomfort felt by passengers when testing suspensions with "skyhook" and "semi-active" control algorithms, and significant noise when switching damping on and off. Experimental bench research of the semi-active suspension by the authors of this article has confirmed the calculated reduction of the amplitudes of vibrations of the suspended mass, accompanied by the presence of shocks and noise at a sharp change of damping in the suspension. Thus, the reduction of amplitudes of vibrations of the suspended mass at this method of regulation leads not to increase, but to decrease of smoothness of a course.

The third disadvantage is that the unsprung mass in the regulation of the algorithms of "skyhook" remains almost without damping, and when reaching its own frequency of unsprung mass of its oscillation on the mathematical model is infinitely increased, which in practice will correspond to the separation of the wheels from the road and the loss of stability and controllability of the vehicle.

In order to solve the problem of stability and controllability of the car, in 1998 the Czech scientist M. Valášek [12] proposed the concept of "groundhook".

The groundhook concept involves a smooth change in damping to bring the standard shock absorber closer to the action of an imaginary shock absorber that links the unsprung mass to the road surface. The main objective of this regulation is to reduce tyre deformation and wheel oscillation. As the theoretical studies of the authors have shown [11], the law of regulation "groundhook" is not workable, because checking the vibrating system, simulating the movement of the vehicle on the road, on the stability of this law of regulation gives a negative result.

Suspensions are used nowadays to simplify the damping control process, where inelastic resistance changes not in the vibration cycle, but depending on the steady-state vibration modes. For example, in the hydropneumatic suspension of a Citroen-C5, which is controlled with the help of an on-board computer, there are 3 modes of operation: comfortable, optimal and sporty. In this case, different from civilian vehicles on combat vehicles, additional adjustment conditions are required, for example, when driving through ski jumps, it is possible to "fly out" the machine and detach all the rollers from the ground, followed by landing, which in order to prevent suspension breakage during compression and rapid damping of vibrations of the hull it is necessary to sharply increase the hydraulic resistance of the suspension of all support rollers. However, the suspensions should have minimal suspension resistance in order to reduce the harmful effects of shaking on the crew when the machine is moving on a relatively flat surface with low unevenness. Solution of these problems with the help of a large number of sensors and on-board computer significantly complicates the suspension, reducing its reliability and significantly increasing the cost. For example, in comparison with the spring unregulated suspension, a Citroen car with a hydropneumatic adaptive suspension "Indractive-2" is more expensive by $5000.
3.2. Regulation of the stiffness of the elastic suspension element

Nowadays the experts in the field of vehicle suspension have shown interest in the possibility of increasing the smoothness of the car by changing the rigidity of the suspension in the cycle of vibration. The most obvious way to change the stiffness of the suspension is the use of additional volume with the possibility of its disconnection and inclusion in the air springs. Such a method of change of suspension stiffness in the cycle of vibrations is considered in many works, in which various algorithms of using the additional volume are proposed and considered [3, 13–15].

It is shown in [13] that high efficiency of damping of vibrations in the air suspension, comparable with the efficiency of hydraulic shock absorbers, can be achieved due to free air flow between the working and additional cavities of the air spring at certain moments of the cycle of vibrations.

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The paper [14] proposes the pneumatic springs with self-regulating air damper in amplitude and direction, as a result of which the damping force is almost always directed against the movement of the suspended mass, which provides effective damping of its vibrations and reduction of energy losses and heating of the suspension.

The algorithm of control of a suspension with S-shaped piecewise linear elastic characteristic of the air spring having two stages of rigidity, has been offered by Takagi A., Yoshimura T. in the Tokushima University (Japan) [15].

The large number of the proposed algorithms is connected with the absence of the theory of optimal regulation of suspension stiffness in the cycle of oscillations.

Studying the possibility of increasing the smoothness of the car's motion by regulating the stiffness of the elastic element, it is necessary to take into account the method of changing the stiffness, as well as the change in the static deformation of the suspension as a result of changes in stiffness. There are three ways to change the stiffness of the suspension:

1) blocking a part of the elastic element used, for example, cutting off a part of the cavity of the working chamber in the air suspension [13], blocking a part of the coils of the screw spring [13, 16, 17], blocking a part of the torsion;
2) use of a spring element that can be switched off in series, e.g. use of a series-connected additional volume in the air suspension [3, 14], installation of a series of additional springs;
3) use of a spring element which can be switched off in parallel, e.g. use of an additional torsion in the torsional suspension.

These methods provide two-stage stiffness, but in the same way you can get a suspension with a higher number of stiffness levels.

Although there are many different ways to change stiffness, there are two basic schemes of two-stage change of stiffness: with constant stiffness of the steps and variable stiffness of the steps. Thus, the suspension with additional elastic element to be installed in series or in parallel with the switchable elastic element has a constant stiffness of steps and belongs to the first type of hangers, and the air suspension with additional volume has no fixed stiffness of steps and belongs to the second type of hangers.

The two-stage suspension with constant stiffness works as follows. The object of vibration protection (vehicle body) is sprung by two successively installed elastic elements — main and additional. The suspension is equipped with a mechanism to block the additional elastic element. When the additional elastic element is blocked, only the main elastic element remains in operation, and the rigidity of the suspension increases. When the elastic element is released, it is included in the work and the rigidity of the suspension is reduced. Thus, this suspension provides almost instantaneous two-stage switching of stiffness that allows to carry out adjustment of stiffness in a cycle of fluctuations of a suspension.

The two-stage suspension with variable stiffness disengages the part of the elastic element that is in the blocking zone when the blocking mechanism is activated. For example, the additional volume in
the air suspension with disconnectable additional volume blocks part of the additional volume of gas that is in the additional volume at the moment of its disconnection.

The researches of the authors of this article have shown that the two-stage suspension with constant rigidity of stages has higher potential vibration-protective properties in comparison with the suspension having variable rigidity of stages which provides good vibration-protective properties only in the field of low-frequency vibrations. The optimum ratio of the stiffness of the main and additional elastic elements in the suspension with constant stiffness of the stages is about 3:1.

The specific feature of the suspension with instant change of stiffness is the discharge of potential energy of the blocked and free elastic elements (or, depending on the design, the sections of the elastic element) at the moment of unblocking the blocked elastic element (section). The instant release of the elastic element (region) in real designs creates a blow at the junction of the elastic element, causing high-frequency vibrations of the elastic element's body. For example, longitudinal spring oscillations in spring hangers. The presence of weights fixed on the springs (separator of the main and additional elastic elements) is the reason of excitation of own oscillations of loads, which does not exclude the own oscillations of springs, which are overtones in relation to the oscillations of the load. The energy of these vibrations is equal to the energy released when unblocking a part of the suspension.

It takes a long time to dampen high-frequency vibrations, so during the switching process the energy of the vibrations will accumulate, which will eventually lead to suspension failure. In order to avoid this, it is necessary to use special damping devices in the suspension with instant change of stiffness or to use a smooth, instantaneous change of stiffness of the suspension.

3.3. Use of dynamic vibration dampers

The dynamic vibration dampers are one of the means of reducing the vibration dynamic loading of various technical constructions and structures. The principle of their action consists in the use of an additional inertial element that affects the object of vibration protection directly or by means of elastic (elastic damping) element in such a way that this effect is directed against the movement of the object of vibration protection in most of the cycle of vibration.

One of the effective ways to reduce wheel oscillations and body accelerations in the field of high frequencies is the use of dynamic vibration wheel dampers (DVWD) in the suspension design [18–24]. Therefore, interest in DVWD has increased recently, but, nevertheless, dynamic dampers have not been widely used, as their introduction leads to complication and weighting of the car suspension due to the presence of additional inertial mass. In addition, due to the relatively large size of DVWD, their arrangement in the serial suspension of vehicles becomes more complicated.

Another use of DVWD, which not only does not increase the unsprung weight of vehicles, but even reduces it, is the integration of a dynamic damper with existing elements of the unsprung weight of the vehicle. As the inertial mass of DVWD it is proposed to use a disc brake caliper, which is installed on both front and rear wheels in modern vehicles. For this purpose, the caliper is mounted on a swivel arm with the possibility of angular movement relative to the wheel axle and is connected to the wheel stand by means of an elastic-damping bond, which is locked during braking and which includes a resilient element and a lockable hydraulic shock absorber. This reduces the unsprung mass by the weight of the caliper, and the mass of the caliper itself becomes a DVWD inertial mass, sufficient to effectively dampen the vibrations of the wheels while the vehicle is in motion. When the vehicle is braked by the pressure of the operating fluid of the brake system, the hydraulic shock absorber is blocked, so the braking properties of the vehicle do not change.

Of course, such a design DVWD makes certain adjustments to the overall design of the disc brake and suspension, but with the right calculation and choice of parameters, this idea is quite feasible and will have a significant effect.

In order to reduce truck body oscillations, which have high rigidity of elastic suspension elements, which is necessary for realization of the given load-carrying capacity of vehicles, it is expedient to use flywheel dynamic dampers (absorbers) of oscillations (inertial-friction or inertial-hydraulic shock absorbers). They due to alternating rotation of the flywheel provide an increase in the reduced mass
and, as a consequence, a decrease in its own frequency of suspension oscillations and a significant increase in the smoothness of the ride. The studies of suspensions with flywheeled dynamic vibration dampers carried out by the authors of this article have shown their high efficiency [22, 23].

4. Conclusions
Thus, it is necessary to solve the following urgent problems in order to improve smooth running and further develop vehicles equipped with suspension:

- search for algorithms of smooth damping control and their design solutions, resulting in increased efficiency of the shock absorber [5, 6];
- development of adaptive suspensions with self-adjustable damping characteristics depending on vibration modes, which do not require external control and energy supply [3, 4, 24];
- development of the basis for the theory of optimal control and energy supply [3];
- search for algorithms of suspension stiffness control and their design solutions, resulting in smoother ride of the vehicle [3, 13, 14];
- development of suspensions in which DVWD are integrated into serial suspensions without increasing their dimensions, for example, by installing air springs with rubber-cord casings in pistons, the variants of which are proposed by the authors [20, 21].
- production and testing of prototypes of inertial-friction or inertial-hydraulic shock absorbers with energy recovery [22, 24].

References
[1] Ryabov I M, Novikov V V, Pozdeev A V 2016 Efficiency of Shock Absorber in Vehicle Suspension Procedia Engineering (International Conference on Industrial Engineering (ICIE-2016) vol 150) ed A A Radionov (Elsevier publishing) pp 354–362
[2] Ryabov I M, Chernyshov K V, Pozdeev A V 2016 Energy Analysis of Vehicle Suspension Oscillation Cycle Procedia Engineering (International Conference on Industrial Engineering (ICIE-2016) vol 150) ed A A Radionov (Elsevier publishing) pp 384–392
[3] Pozdeev A V, Novikov V V, Diakov A S, Pokhlebin A V, Ryabov I M, Chernyshov K V 2013 Adjustable pneumatic and hydro-pneumatic springs of motor vehicles suspensions (Volgograd, Volgograd State Technical University) 244 p
[4] Pokhlebin A V, Pozdeev A V, Golyatkin I A 2016 Control algorithms of inelastic resistance forces of hydropneumatic springs 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) (Chelyabinsk, Russia) Publisher: IEEE 6 p
[5] Ryabov I M, Chernyshov K V, Pozdeev A V 2017 Vibroprotective and Energetic Properties of Oscillating System Equivalent to Vehicle Suspension with Pendular Regulator on Shock Absorber Procedia Engineering (International Conference on Industrial Engineering (ICIE 2017) vol 206) ed A A Radionov (Elsevier Ltd.) pp 392–400
[6] Ryabov I M, Chernyshov K V, Pozdeev A V 2017 Vibroprotective and Energetic Properties of Vehicle Suspension with Pendular Damping in a Single-Mass Oscillating System Procedia Engineering (International Conference on Industrial Engineering (ICIE 2017) vol 206) ed A A Radionov (Elsevier Ltd.) pp 519–526
[7] Furunzhiev R I 1965 Investigation of some issues of damping vehicle vibrations Dissertation of Candidate of technical sciences (Minsk)
[8] Pontryagin L S, Boltyansky V G, Gamkrelidze R V, Mishchenko E F 1976 Mathematical theory of optimal processes (Moscow, Nauka) 392 p
[9] Karnopp D C, Crosby M J 1973 The Active Damper — a New Concept for Shock and Vibration Control 43-rd Shock and Vibration Bulletin, Part H, June pp 46–73
[10] Karnopp D C, Crosby M J, Harwood R A 1974 Vibration control using semi-active force generators Transactions of the ASME (Journal of Engineering for Industry vol 96) pp 619–626
[11] Chernyshov K V, Ryabov I M, Pozdeev A V, Pylinskaya T V 2018 Analysis of “skyhook” and “groundhook” principles of damping control in the vehicle’s suspension *Truck: transport complex, special equipment* (Moscow, Russia) 10 pp 3–6

[12] Valášek M et al. 1997 Extended ground-hook — new concept of semi-active control of truck’s suspension *Vehicle system dynamics* vol 27 5-6 pp 289–303

[13] Kalashnikov B A 2008 Objects damping systems with discrete switching of elastic elements (Omsk, Omsk State Technical University) 344 p2008

[14] Pozdeev A V, Diakov A S, Novikov V V, Riabov I M 2013 Self-adjustable dual-chamber pneumatic springs with switching of chambers *Truck: transport complex, special equipment* (Moscow, Russia) 9 pp 2–5

[15] Yoshimura T, Takagi A 2004 Pneumatic active suspension system for a one-wheel car model using fuzzy reasoning and a disturbance observer *Journal of Zhejiang University SCIENCE* 5(9) pp 1060–1068

[16] Chernyshov K V, Ryabov I M, Pozdeev A V 2019 Potential Vibration Isolation Qualities of Suspensions with Two-Step Stiffness Control in Oscillation Cycle *Proceedings of the 4th International Conference on Industrial Engineering (ICIE 2018)* (Moscow, Russia) ed A A Radionov (Lecture Notes in Mechanical Engineering (LNME) Springer) pp 437–448

[17] Chernyshov K V, Ryabov I M, Pozdeev A V 2019 Theoretical Foundations of Optimal Two-Step Control of Suspension Stiffness of Transport Vehicle in Oscillation Cycle *Proceedings of the 4th International Conference on Industrial Engineering (ICIE 2018)* (Moscow, Russia) ed A A Radionov (Lecture Notes in Mechanical Engineering (LNME) Springer) pp 421–436

[18] Novikov V V, Pozdeev A V, Chumakov D A, Kovalev A M 2017 The joint operation of the pneumatic suspension of the vehicle with a dynamic vibration damper and a hydraulic shock absorber *Mechanical Engineering Bulletin* 7 pp 34–39

[19] Ryabov I M, Chernyshov K V, Kovalev A M 2010 Potential vibroprotective properties of a vehicle suspension with a dynamic vibration damper of wheels *Automotive industry* 12 pp 13–16

[20] Novikov V V, Pozdeev A V, Ryabov I M, Chernyshov K V, Chumakov D A 2016 *Pneumatic suspension* (RU Utility model 167265)

[21] Novikov V V, Pozdeev A V, Ryabov I M, Chernyshov K V, Chumakov D A 2016 *Pneumatic suspension* (RU Utility model 169805)

[22] Ryabov I M, Novikov V V, Pozdeev A V, Chernyshov K V, Mitroshenko A S 2013 Types of designs of inertial-friction shock absorbers, their modeling and testing *Tractors and agricultural machinery* 4 pp 23–26

[23] Ryabov I M, Chernyshov K V, Pozdeev A V 2015 Comparative evaluation of the vibration isolation properties of a suspension with different flywheel dynamical absorbers of the car body oscillations *Procedia Engineering* (International Conference on Industrial Engineering (ICIE-2015) vol 129) ed A A Radionov (Elsevier publishing) pp 480–487

[24] Novikov V V, Ryabov I M, Chernyshov K V 2009 *The vibration isolation properties of the motor vehicles suspensions* (Volgograd, Volgograd State Technical University) 338 p