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ANALYSIS OF MODERN INVESTIGATIONS OF VIBRATORY PROCESSES OF WHEELED VEHICLES

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Abstract. The history and modern tendencies of development of cushioning systems are analyzed in this paper. The development of mathematical modelling as a process is denoted, the methods and means are described and the necessary information of model choosing is presented. It is focused on the development of simulation modelling. The approaches of researchers, recommendations, indexes and specific features of evaluation of motion evenness are described.

The works of many scientists are dedicated to analysis of car vibrations, evaluation of motion evenness and vibration-proof features. Many of them are devoted to investigation of vibrations, to optimization of basic design parameters of the cushioning system of cars and to development of new cushioning systems which allow reducing of vibratory overloading of trucks of general purpose. Taking into account the problems of motion evenness from the point of view of vibration of cushioning parts, the works of scientists are based on the linear theory of cushioning and the simplest one-mass car models are considered. It is also established that the drawback of usage of such theory consists in the fact that it is impossible to overview separately the vibrations of cushioning parts, which weight transfers to elastic elements of the suspension, and non-cushioning parts. The overview of scientific works dedicated to investigation of dynamics of wheeled vehicles allows to show the limited possibilities of traditional passive suspension system according to continuously increasing requirements to modern structures and to substantiate the necessity of usage of controlled cushioning systems. Among the existing variants of controlled cushioning systems, the half-controlled systems, which are the most optimal from the point of view of motion evenness increasing, energy consumption, complexity of structural implementation and usage safety, are of the greatest interest nowadays.

On the basis of analyzed materials, it may be concluded that there exists a great amount of scientific investigations in the field of motor vehicles vibrations many of which are devoted to improvement of vibration-proof features of cars. Also a number of works are dedicated to investigation of vibratory overloading of industrial, construction and agricultural motor vehicles which are engaged in transportation of cargo of general purpose. However, too small attention is payed to development of techniques of determination of design parameters of cushioning systems of trucks which are engaged in transportation of cargo of special purpose, for example, cars transportation, where essentially greater attention should be payed to vibratory loadings which act upon such cargo during uneven motion.

Keywords: cushioning system, vibratory loading, simulation modelling, motion evenness, suspension system, wheeled vehicle.

Introduction

The works of many scientists are dedicated to analysis of suspension vibration of wheeled vehicles, to evaluation of motion evenness and their vibration-proof features [1]. These investigations may be divided into three main areas: investigation of road microprofile (microcontour), of vehicle vibrations and of human perception of vibrations or of cargo preservation. However, it is necessary to denote that some differences in the subject terminology are observed in modern scientific literature. This is mostly related with the usage of foreign investigations in the works of domestic scientists, incorrect translation etc. It is expedient to mention the existence of well-known standards, particularly the standards SAE (Society of Automotive Engineers) J670e [2] and ISO (International Organization for Standardization) 8855 [3], which determine basic concepts that are used for analysis of wheeled vehicle dynamics. Also there exists the new version of SAE J670e [4].

Problem statement

The passive systems of cushioning in which the elastic and damping characteristics remains unchangeable during the wheeled vehicle motion are the most widespread nowadays. This is caused by the comparatively simple and reliable structure of such systems and by no need for external energy sources. However, the potential of such systems to provide ever-increasing requirements for the motion evenness almost reached its maximum. That's why, the actual investigations consist in improvement of cushioning systems in order to ensure the possibility of controlling of their elastic and damping elements during the wheeled vehicle motion.

Analysis of modern information sources

In their historical development the investigations of wheeled vehicles vibrations have passed a number of successive stages which started from the considering of a car as a material point (particle) to considering of complicated dynamic system with concentrated masses and their displacements. The works of Ya. M. Pevzner, A. A. Silaiev, N. N. Yatsenko, R. V. Rotenberg, A. A. Khatchaturov etc. were dedicated to the problems of investigation of vibration processes of wheeled vehicles. In the works of these authors the investigations were carried out by substituting of a wheeled vehicle by some equivalent vibrating system for which the mathematical model in the form of motion equations was deduced, solved and analyzed. In essence, the investigations were carried out by means of the problem solving under the deterministic approach when the microprofile (microcontour) is defined by the prescribed function or by means of the usage of statistic approach when the disturbance caused be the road shocks is described by the random function.

However, the overview and analysis of literature sources [5] have shown that just during the last few decades the significant efforts in research, development and design of the suspension of wheeled vehicles have been made.

The purpose and problems of research

The purpose of the article consists in analysis of modern investigations of vibration processes of wheeled vehicles. To achieve it we must analyze current tendencies of development of cushioning systems and overview the investigations of dynamics of wheeled vehicles, their modelling, designing and testing of separate elements of these systems.

Main material presentation

The published scientific papers describe more complicated and combined passive suspensions which can ensure a compromise between motion evenness and handling of wheeled vehicle [6] and widely present various classes of controlled cushioning systems, such as adaptive, active, semiactive and partly active suspensions, and systems of ground (road) clearance changing [7–9]. Thus, in the works [10–12] the thorough review of investigations of wheeled vehicles dynamics and one-mass models of wheeled vehicles with various types of cushioning systems (Fig. 1) are presented.

The passive system of vibration isolation is traditionally the simplest method of dynamic system protection against vibrations which has the ability to accumulate energy with a help of a spring and dissipate it with a help of a damper. This suspension system (Fig. 1, *a*) is linear and consists of parallel placement of spring and damper and is based on the principle of energy dissipation in a damper, which doesn't need the external energy sources for its operation. When investigating these suspension systems, the main attention is payed to the searching of compromise between motion evenness and comfort [13]. Whereas the parameters of stiffness and damping are fixed, the problem of choosing of optimal parameters of the system is reduced to finding their optimal values in order to achieve acceptable behavior of the machine throughout the whole range of operating frequencies. So, the development of passive cushioning system with excellent indexes of motion evenness, stability and handling is impossible.

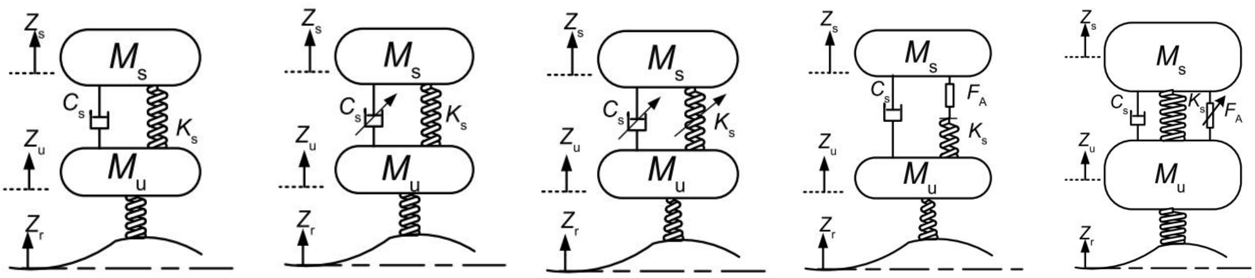


Fig. 1. *Classification of cushioning systems: a – passive; b – semiactive; c – adaptive; d – partly active; e – active*

The high requirements to cushioning systems which are presented in such regulatory (normative) documents as ISO 2631-74, GOST 12.1.012-90, OST 37.001.275-84 encouraged further development of new dynamic systems that ensured appropriate indicators of motion evenness and vibration isolation. Whereas the passive cushioning system requires the compromise between motion evenness, stability and handling, which may not be always optimal, so the further investigations were directed on development of controlled suspensions of various variants of their realization (Fig. 1, *b*–*e*). The main aim of their usage consists in elimination of drawbacks of passive cushioning systems.

Various variants of controlled cushioning systems and the corresponding technology (Table 1) are presented in the work [14].

Semiactive cushioning systems consist of elastic and damping elements, the characteristics of which may change with a help of external energy source. This allows continuous or discrete changing of their characteristics with a frequency of 30-40 Hz, which is sufficient for effective damping of vibrations.

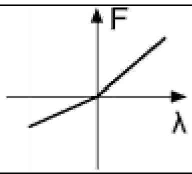
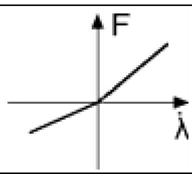
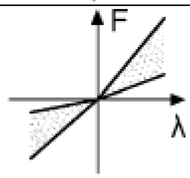
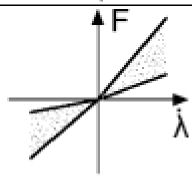
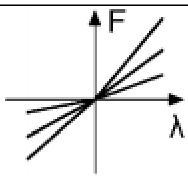
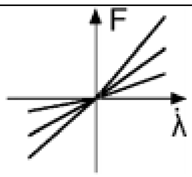
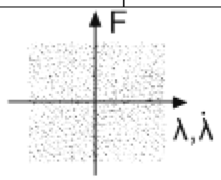
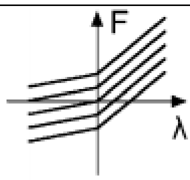
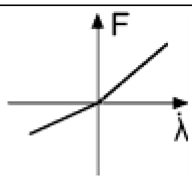
When investigating the semiactive cushioning systems (Fig. 1, *b*) it is suggested to install the regulation element – damper without usage of any external energy sources [15]. The regulated throttle (choke) of various variants of realization: viscous, viscoelastic, friction, magnetorheological, electrorheological, inertial etc., should be installed in the structure of the damper [16]. The coefficient of damping is being continuously regulated from its minimal to its maximal value depending on the speed of wheeled vehicle motion. The typical examples of semiactive systems are suspensions of BMW cars of 7 series, Porsche 911 and Mercedes Benz E-class.

Adaptive cushioning systems (Fig. 1, *c*) allow the changing of stiffness and damping parameters according to the adopted control algorithm for some discrete levels in response to changing traffic conditions [17]. In these systems the change of characteristics of actually passive elastic and damping elements occurs depending on the pressure in the braking system, accelerator pedal position, steering wheel rotation angle, motion speed etc. Adaptive systems don't continuously adapt to changing conditions during some cycles of suspension vibrations. The speed (rapidity) of such systems usually is in the range of 1–5 Hz, which allows to ensure effective control of low-frequency vibrations of cushioned masses. The typical examples of adaptive systems usage are the suspension of Porsche Panamera car of the model of 2009 year.

The executive drive in different realization versions: pneumatic, hydraulic, hydro-pneumatic, piezoelectric or electromagnetic with variable stiffness and damping parameters may be installed in active cushioning systems (Fig. 1, *d*, *e*) [18]. Active systems are divided on the system with narrow (partly active) and wide (fully active) range of operation frequencies of controlling device similar to the adaptive and semiactive systems. In fully active cushioning systems there are no passive elastic and damping elements, so the cushioned masses of the machine are attached to the wheels with a help of non-elastic links. Such systems effectively absorb the vibrations of approximately 30 Hz frequency which in turn makes it comfortable to overcome single inequalities. The operation of such system requires an external energy source (compressor or pump) with corresponding system of controlling methods, in the base of which the methods of fuzzy logic, neural control methods, linear quadratic regulators (controllers) etc. may be used [19].

Table 1

Classification of controlled cushioning systems

System class	Dependence of changing of the load *F* in the elastic element from its deformation l	Dependence of changing of the load *F* in the damping element from its deformation speed $\dot{l}$	Range of frequencies of the control device operation, *Hz*	Necessary power, W
Passive			-	-
Semiactive			30–40	10–20
Adaptive			1–5	10–20
Partly active			1–5	1000–10000
Active			20–30	> 10000
System of ground (road) clearance changing			0.1–1.0	1–5

The investigations of vibrations of wheeled vehicles are widely presented for different mathematical models: 1/4 of a car, 1/2 of a car or the space (three-dimensional) model [20; 21]. They are presented as a system of differential equations, deduced with a help of the principle of d'Alembert or Lagrange equations, which reflect the structure features with some adopted assumptions and present the relationship between their separate parts. At the input of the system the input signal is applied as a function of road inequalities or unit impulse.

The information which deals with the investigations of wheeled vehicles vibrations is presented beginning from the simplest mathematical models, which mainly deals with linear one-mass system with one degree of freedom when moving through the unit or periodically placed road inequalities, to complicated multi-mass mathematical models taking into account the cushioned and non-cushioned masses, biodynamic model of human body, load (cargo) influence, stiffness and damping characteristics of suspension and tires. After analyzing of mathematical model of wheeled vehicles it is necessary to mention that one-mass motor vehicles models are used in most cases to study the system response to an input signal as disturbance using the Heaviside function. In such a way, the transfer characteristic of the system may be received with a help of which we may determine the system response to input disturbance of arbitrary shape and form an amplitude-frequency characteristic (response).

In flat multi-mass model of a car the moment of inertia of cushioned mass about the axis that is perpendicular to the plane of the figure should be added. The investigation of vibrations is carried out for such typical cases: passing of short localized road shocks, the influence of which on the system wheels has striking (shock) nature; passing of localized and periodic road shocks of sinusoidal shape; passing of the road shocks of arbitrary shape. The input signal is presented as the autocorrelation function; the transfer function is being received on the basis of differential equations of free oscillations of wheeled vehicle; the amplitude-frequency characteristics (responses) are formed and the values of mean accelerations of centers of masses of the system are obtained, which in turn depend on the autocorrelation function of road microprofile and on transfer function of the system. For example, in the work [23] the flat model of wheeled vehicle is presented in the form of 14-mass dynamic system in order to investigate random vibrations in vertical plane during uniform motion which is characterized by the prescribed function of microprofile. There is mentioned in the work [23] that the presence of the load (cargo) may be used as means of passive dynamic vibration damping (if the correct design and assembly parameters of the system are chosen). Thus there will be a certain resonance speed, which will maximally show this effect.

The evaluation of influence of structure of the cushioning system on the motion evenness, stability and handling requires the forming of space (three-dimensional) model. For example, in the work [24] the 9-mass three-dimensional (space) model of a car is presented taking into account biodynamic models of driver and passengers, which has 11 degrees of freedom. It consists of one cushioned part which represents a frame of a car, and of four non-cushioned masses which represent the wheels assembled with springs and shock absorbers (dampers), and four separate masses which represent biodynamic models of human body.

Because there is a wide representation of mathematical models of wheeled vehicles of different complexity, further research is aimed at developing of systems of cushioning control.

One of the spheres of further investigation of machines dynamics is solving of problems of cushioning systems active control in order to limit the range of operation frequencies during the motion. In the work [25] the problem of suspension control was investigated in order to limit its operation frequency in the range of 4–8 Hz according to a comfortable perception of the human body [26]. The two-mass model of a car was adopted as an investigation object and the method of controlling of active cushioning system was developed with a help of Kalman-Yakubovich-Popov theorem (KYP-lemma) [27].

The research of active cushioning systems with the devices of road microprofile scanning is also actual. In the work [28] the developments of prior road surface sensing (sounding) and usage of obtained parameters of road mocroprofile that are being received with a help of composite sensor, for which the output signal represents an autocorrelation function of road shocks, are presented. The space (three-dimensional) model of a car with active system of suspension which may change the stiffness and damping parameters according to the characteristics of road microprofile during the motion is being considered as an investigation process. In practice, the results of investigations are being implemented into the elements of ABC (Active Body Control) system, which is adapting the suspension operation according to the road (traffic) situation.

The investigations of active cushioning systems which use the methods of fuzzy logic are also presented in literature. In the work [29] the model of 1/4 of a car with fuzzy logic controller is presented. The operation of controller allows to ensure the high level of motion evenness, necessary accuracy of stability and handling. This device sets the algorithm of the active suspension operation in response to body roll changing.

The investigations of active cushioning systems with the usage of PID (proportional-integral-derivative) controllers have also gained ground. The essence of PID controller operation consists in controlling of active suspension operation depending on the difference between the given values of vibrations frequency and the measured ones. As a result, this mechanism has to ensure such operation of suspension, when the measured vibrations frequency equals to the given one. For example, in the work [30] the two-mass model of a car with active cushioning system and with developed suspension control scheme that is effective concerning motion stability, handling and evenness is presented. The comparison of this system with passive cushioning system (Figure 1, a) was carried out and the conclusions that this technology allows to reduce the vibrations by 75.9 % were made.

The modern state of motor vehicles theory is also characterized by intensive development of simulation modelling of their motion, by the possibility of analyzing the structure perfection and optimization of system parameters on the basis of wide usage of science and technology achievements and multifaceted possibilities of computer technology at all stages of design and research. This is prospective, advantageous and expensive research tool that can be afforded mostly by powerful scientific institutions and private manufactures of vehicles. Thus, for example, the software NEWEUL 83 [31] was developed for carrying out mathematical modelling and multivariate calculations with possibility to change the number of degrees of freedom of the system elements and the characteristics of nonlinearity; the developments of the Talbott Associates firm (USA) allow to conduct computer modelling of the motion processes and handling of the road train (articulated vehicle) with various trailed links [32]; the vibrations of vehicle, safety, structural optimization of dynamics may be investigated with a help of specially developed programs DYNA 3D, PAMCRASH i RADIOSS [33]; the program OPTIM [34] is used for research of motion stability and handling of a car or a road train; the developments of the Paccar firm (USA) may be used for road train dynamics modelling, motion evenness prediction, choosing of criterions for suspension designing, correcting of unacceptable parameters of some operational features; various software for finite-element analysis (Ansys, Nastran etc.) and the programs for mechanism kinematics analysis (Adams) are used for solving various problems of dynamics and dynamic analysis of the structure of wheeled system; the software IMITA, COMPACT, Design Studio, Unigraphics, Most-7.2 etc. are also widely used.

In these means of research, the object and object-oriented programming languages are used. This allows to essentially increase the level of unification for reuse of not only programs, but also for reuse of projects that leads to formation of the development environment. Object-oriented systems are often more compact and this provides the decreasing of program code, project price reduction by using previous developments. The models of the systems are formed on the basis of stable intermediary results that simplifies the process of changes making because the system is being formed gradually and doesn't need the revision (adaptation, remaking) when significant changes of input parameters take place. This allows the opportunity to reduce the risk of errors creeping in the process of complicated systems modelling, because the process of integration extends throughout the whole time of development and is not a single research. In future, there is an opportunity to extend it by the blocks of parametric and structural optimization of new physical principles of operation of units and assemblies of the system.

The above mentioned software is too expensive or is a property of developers which specialize in such calculations. That's why in the conditions of limited budget or of the lack of engineers and specialists in computer programming the software MATHCAD, MAPLE, MATLAB, etc. is usually used. MATLAB software is used for designing and investigation of complicated dynamic systems, modelling, analysis and visualization of dynamic processes. Taking into account the fast development of possibilities of computer technologies we may obtain the results considering the larger amount of input parameters when describing the motion of motor vehicle. This, of course, reduces the time needed for development and designing of new machinery or for improvement of existent one and essentially simplify experimental investigations.

During the process of modelling the solving of the following problems is the most interesting: studying of dynamic characteristics of the system; calculation of statistic characteristics of vibrations during the system motion when the random disturbances caused by the road shocks act upon it; investigation of the influence of structure parameters on vibratory processes and their optimization; studying of dynamics of separate links of the system in order to obtain more simple equivalent schemes for describing of their operation; combining of some separate objects of the road-tire-car-driver system into the single complex including the models of other links of this system. Nowadays the most actual problem consists in development or improvement of mathematical model of motion and its realization as a software where the special attention should be focused on the description of the practical issues, especially, of the issues of addition and changing of the design scheme according to the specified criteria in order to speed up the work on the stage of designing, to reduce the number of experimental samples (models) and, finally, to improve the quality and efficiency of experimental and designing works.

Conclusions

Thus, nowadays there is a large number of scientific investigations of vibratory processes in wheeled vehicles, most of which are focused on improving of the vibration-proof features of cars. Also the investigations of vibration overloading of industrial, building and agricultural commercial vehicles (trucks) of general purpose are being carried out. However, rather little attention is paid to developments of techniques of determination of basic structural parameters of cushioning systems of trucks, which are used for transportation of cargo of special purpose including motor vehicles, where the major attention should be paid to vibration overloadings which are being transferred to the cargo and to the vehicle.

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