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ANALYSIS OF METHODS AND MODELS FOR STUDYING VEHICLE SUSPENSION SYSTEMS

The design of the car's suspension has the greatest impact on its performance properties: smooth ride, stability and handling. Increasing the smoothness of the ride provides comfortable sanitary conditions in the driver's and passengers' seats. As a rule, high smoothness of the ride can be achieved by reducing the rigidity of the elastic device and the damping coefficient of the shock absorber and, accordingly, increasing the suspension travel. Therefore, it is important to identify the disadvantages of different types of suspensions, classify them and further study their properties. In the development of technical solutions for the elements of the suspension systems of military vehicles and methods for studying the processes and states of operation of the suspension systems, there are a number of problems that need to be solved. This is the absence of an orderly system approach that comprehensively describes the process of choosing technical solutions for these elements based on the formulation of mathematical models describing processes and states for the synthesis of the structure and the selection of parameters. During the analysis, it was found that the existing mathematical models of processes and states are sometimes either unreasonably simplified or too cumbersome. An analysis of methods and models of research of car suspension systems has been carried out to determine the advantages and disadvantages of different types of suspensions. The analysis of suspensions (double-link, multi-link, adaptive, dependent, semi-dependent) was carried out on the following grounds: simplicity, compactness, reliability, noise and vibration insulation, controllability, the possibility of installing a drive axle, cheapness, cheap maintenance. They were classified as mechatronic systems: passive suspension systems, adaptive suspension systems, suspension systems with the ability to quickly adjust damper characteristics, slow-acting suspension systems, fully active suspension systems The advantages and disadvantages of different types of suspensions are determined, their classification as mechatronic systems are necessary for subsequent modeling of operation and determination of operational properties.

Keywords: car suspensions, suspension systems, mechatronic systems, smoothness, research models.

INTRODUCTION

The design of a vehicle’s suspension system has the greatest influence on its operational properties such as ride comfort, stability, and handling. Improving ride comfort means reducing the amplitude of vibrations and vibration acceleration at the driver’s and passengers’ seating points. Humans perceive vibrations of different frequencies differently; therefore, it is more important to dampen vibrations of certain frequencies over others. The characteristics of the sprung mass vibrations depend on the input effects (road micro-profile, vehicle speed) and the transfer function of the suspension, which is determined by the parameters of the elastic and damping elements. Generally, a high level of ride comfort can be achieved by reducing the stiffness of the elastic element and the damping coefficient of the shock absorber, along with increasing the suspension travel.

AIM AND OBJECTIVES OF THE STUDY

The aim of this article is to analyze the methods and models used for studying vehicle suspension systems, to identify the advantages and disadvantages of different types of suspensions, and to classify them as mechatronic systems.

To achieve this, it is necessary to review and analyze the methods and models used for studying vehicle suspension systems, determine the strengths and weaknesses of different types of suspensions, and classify them to enable further modeling of their operation and evaluation of their performance characteristics.

LITERATURE REVIEW AND PROBLEM STATEMENT

During the design of vehicle suspension systems, various research models and methods are applied and improved, with the goal of optimal suspension system design [1-11].

In [5], the influence of road characteristics on the parameters of the torsion suspension system of an electric vehicle was analyzed. These characteristics include the working travel of the suspension and the dynamic load on the wheel. Optimization of the main parameters of the torsion element was carried out.

Among other types of suspensions, systems with hydraulic shock absorbers are studied [12]. Hydraulic shock absorbers absorb significant power through the substantial increase in the dynamic travel of the suspension, which is not possible with conventional designs.

Reference [3] established that typical suspension systems cannot meet the stringent requirements posed to modern light armored vehicles (LAVs). The main contradictions encountered during synthesis are outlined, and possible ways to resolve these contradictions in suspension design are discussed.

Works [13,14,15] investigate the vertical vibrations of wheeled vehicles, identifying the conditions for the occurrence of resonance phenomena (the dependence of resonance amplitude on the restoring force of elastic dampers) for different types of suspensions.

In [16], a theoretical analysis of the influence of LAV suspension parameters on the oscillations of the vehicle body along with its weaponry was conducted. A comparison between linear and nonlinear suspension system characteristics is presented, based on the efficiency criterion for shooting performance.

Based on the conducted review, it was found that the existing theoretical foundation for solving the problems of parametric synthesis of suspension systems is incomplete. Available mathematical models require further improvement.

Papers [15-17] consider mathematical and physical models of dynamic suspension processes. Based on the mathematical models described in [18,19], a system of differential equations representing the suspension processes is formulated. The difference between the models in [17] and [18,19] lies in the additional generalized coordinates and the description of the elastic and damping connections between suspension elements.

The input data is the mass-geometric characteristics of the car, the design of the suspension and its elements, driving modes, road profile, etc., and the result is acceleration, speed, movement, power parameters of the suspension and body.

In [20], a mathematical model describing the dynamics of the "suspension-body-combat module" system was proposed. A key feature of this model is the ability to account for parametric dependencies of the coefficients in the system of algebraic-differential equations on the generalized parameters of a specific vehicle suspension. The model output provides a parametric relationship between the system's dynamic variables and a set of critical parameters.

Parametric and structural optimization, as well as the synthesis of new physical principles for the operation of suspension system components, are considered in [21]. A mathematical model was developed to study the stress-strain state of a vehicle body. Its distinctive feature compared to other models is the structural formulation of the problem, allowing the derivation of design solutions based on the analysis of the stress state simulation results under firing conditions and specified variations of a defined set of design parameters. This approach is also applied to problems involving periodic impulse loads for analyzing strength and stiffness characteristics.

In [22], it is noted that when formulating mathematical models of dynamic processes in military vehicles, two components must be considered: the continuous and the discrete. The first is used for modeling the stress state of the light armored vehicle (LAV) body, and the second for modeling the equipment, suspension, and tires. This enables the solving of dynamic process analysis tasks in LAV bodies. By combining the finite element method and the generalized parametric modeling method, a technique for creating a set of parametric models of dynamic processes in LAV bodies is presented in [22].

In [4], models and research methods are described that allow for the development of recommendations regarding design solutions for LAV suspension systems. Traditional modeling methods [23] generally analyze the stress state of a torsion bar. Improved computational schemes combined with the finite element method are commonly used when analyzing the torsion bar foundation. The paper presents the task of improving algorithms, models, and methods for studying the stress state of the torsion bar, considering elastic-plastic deformation throughout the entire structure. A generalized parametric approach based on the methods of variational inequalities theory, elastic-plastic deformation, and finite element techniques was adopted. The resulting model is parametric.

To this day, the oscillatory effect of the vehicle body remains a significant problem for the automotive industry. This effect can occur when a vehicle moves over uneven surfaces or when disturbances are generated by an installed weapon system. Under the influence of body oscillations, the vehicle may behave unpredictably, potentially leading to accidents.

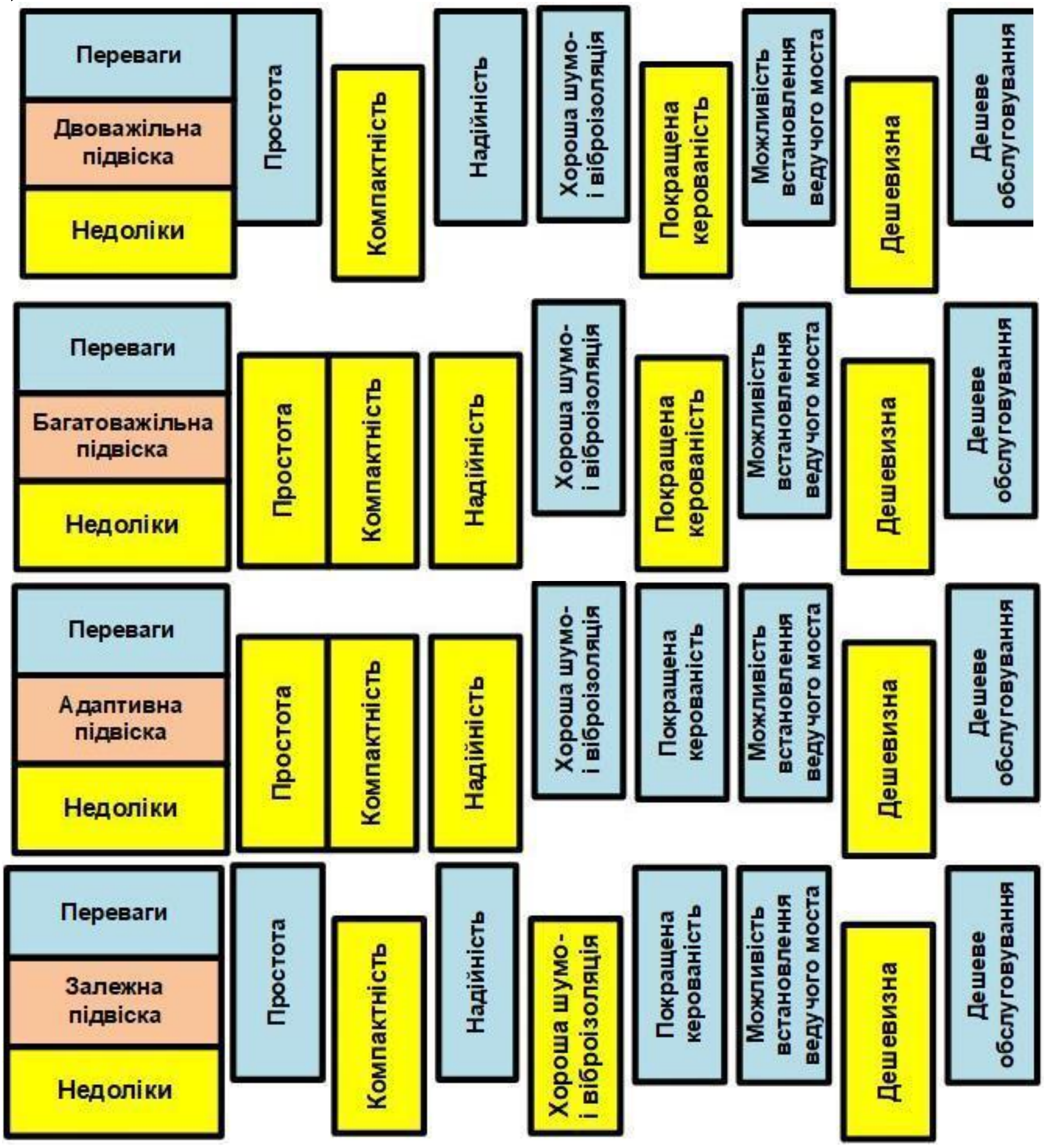
A significant number of studies by national scientists [17;18;24] have been devoted to determining the oscillatory capabilities of a vehicle's sprung masses. Based on the analysis of available literature and publications, calculation methods for the stiffness of sprung masses for major types of suspensions were reviewed. Existing methods for calculating the oscillations of vehicle sprung masses generally do not consider the vehicle being in a static state. Changes in the design of modern vehicles, both domestic and foreign, were analyzed [19;23]. The shift in the center of gravity depending on the tactical and technical characteristics of installed non-standard weapon systems was also studied [16;21].

RESEARCH RESULTS

The conducted review highlighted the relevance of the body oscillation problem and emphasized the need for solutions to reduce its impact on vehicle movement. The findings also confirm the importance of research aimed at developing new technologies to enhance vehicle safety and ensure the effective use of mounted weapon systems.

Mathematical models are used to investigate the influence of suspension parameters on vehicle body oscillations along with equipment loads. It is particularly important to determine resonance phenomena that affect the strength characteristics of vehicle elements, especially the body. Tasks involving periodic impulse loads are critical, as they have a significant impact on the vehicle's reliability.

Different designs offer various advantages and disadvantages. These can be categorized into constructive (simplicity, compactness, good noise and sound insulation, ability to install a front driving axle), operational (improved handling, low-cost maintenance), and economic (low manufacturing cost) aspects (Figure 1).



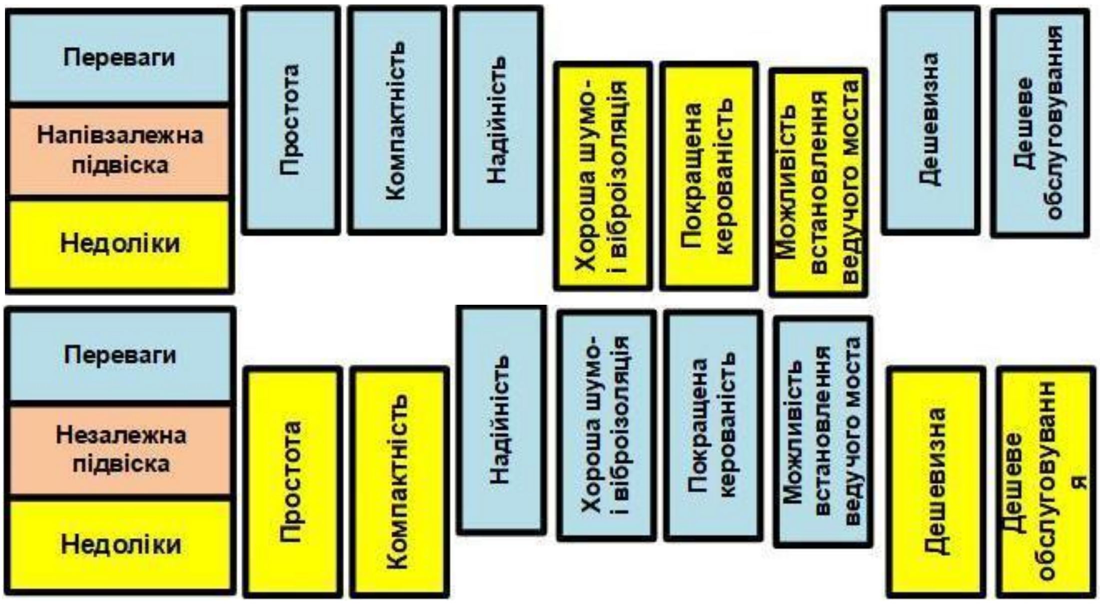


Figure 1 – Advantages and Disadvantages of Different Types of Suspensions

Mechatronic suspension systems can be classified according to the types of actuators they use, including actuator bandwidth, power consumption, and control range, that is, the limits of the forces generated by the actuators. Accordingly, mechatronic suspension systems can be divided into five groups:

1. Passive Suspension Systems (Figure 2) operate quasi-statically, maintaining a constant distance between the chassis and the road to compensate for different vehicle load levels. The leveling system may be based on air springs and compressors. Thus, a soft, comfort-oriented suspension setup with sufficient travel can be achieved regardless of the vehicle load level. Their power consumption typically ranges between 100–200 W.

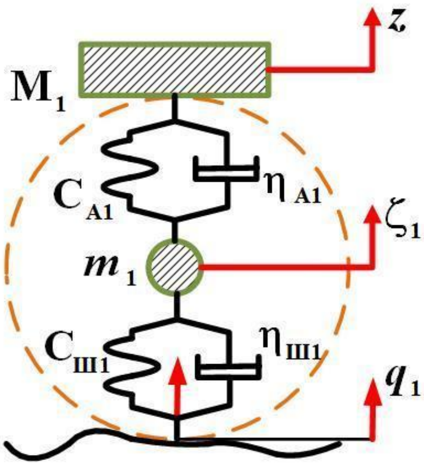


Figure 2 – Model of a Passive Suspension System

where: M_1 – sprung mass per wheel; m_1 – unsprung mass per wheel; СШ$_1$ – vertical stiffness coefficient of the tire; СП$_1$ – vertical stiffness coefficient of the suspension spring element; ηA$_1$ – damping coefficient of the suspension damper; ηШ$_1$ – damping coefficient of the tire; z – vertical position of the vehicle's center of mass per wheel; ξ_1 – vertical position of the unsprung mass; q_1 – real-time ordinate value of the road microprofile at the wheel contact.

2. Adaptive Suspension Systems (Figure 3) are defined in the literature as systems that slowly adjust the characteristics of springs and dampers. Changes are planned, for example, depending on the vehicle speed to lower the center of gravity for more sporty road holding. Their energy consumption mainly depends on the energy required to change the spring stiffness. This thesis presents adaptive suspension control concepts aimed at achieving high dynamic adaptability to current driving conditions.

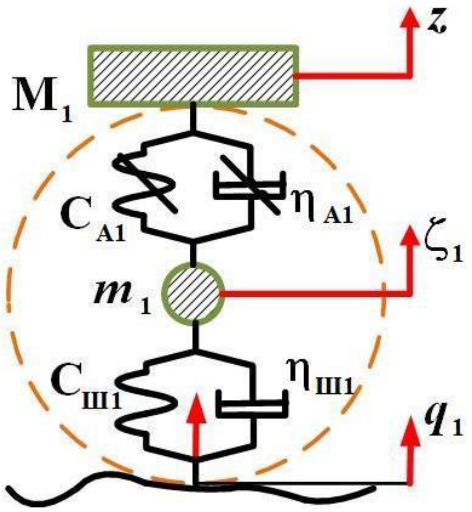


Figure 3 – Model of an Adaptive Suspension System
where: СП_1 – variable vertical stiffness coefficient of the suspension spring element; ηA_1 – variable damping coefficient of the suspension damper.

3. Semi-Active Suspension Systems (Figure 4) are capable of quickly adjusting damper or spring characteristics. A main attribute of semi-active systems is that the force generated by the semi-active element depends on the direction of relative movement. Semi-active dampers can adjust energy dissipation levels but cannot inject energy into the system. Accordingly, they have very low power consumption, about 20–40 W per damper. Their bandwidth reaches up to approximately 40 Hz. An example is the ZF Lemforder GmbH semi-active anti-roll bar with switchable additional springs.

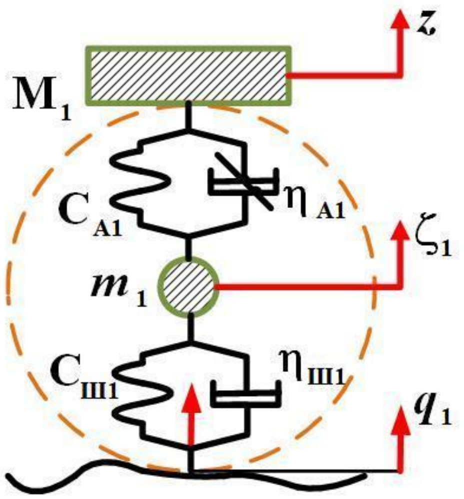


Рисунок 4 – Модель напівактивної системи підресорювання
де ηA1- Figure 4 – Model of a Semi-Active Suspension System
where: ηA_1 – variable damping coefficient of the suspension damper.

4. Slowly Active Suspension Systems (Figure 5) (also called low-bandwidth active systems) represent a class of active suspensions characterized by an additional actuator (e.g., an electric linear motor or a hydraulic cylinder) integrated into the suspension to generate suspension forces independently of the relative motion between the chassis and the wheel. The bandwidth of these systems is about 5 Hz. Typically, actuators are serially connected with the primary spring and may tend to "amplify" if bandwidth is exceeded. Their power requirements are about 1–5 kW.

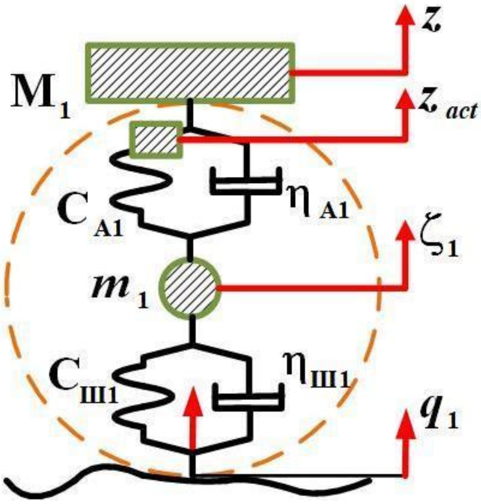


Figure 5 – Model of a Slowly Active Suspension System
where: zact – displacement of the active element.

5. Fully Active Suspension Systems (Figure 6) (high-bandwidth active systems) replace or supplement the passive damper with an actuator capable of operating at 20 Hz or higher. Actuators are mounted in parallel with the primary spring, and passive dampers may sometimes be absent (though they might still be included in the mathematical model to account for frictional effects). A major drawback is their high energy consumption, ranging from 4 to 20 kW. Examples of active elements include pneumatic cylinders or springs with variable stiffness.

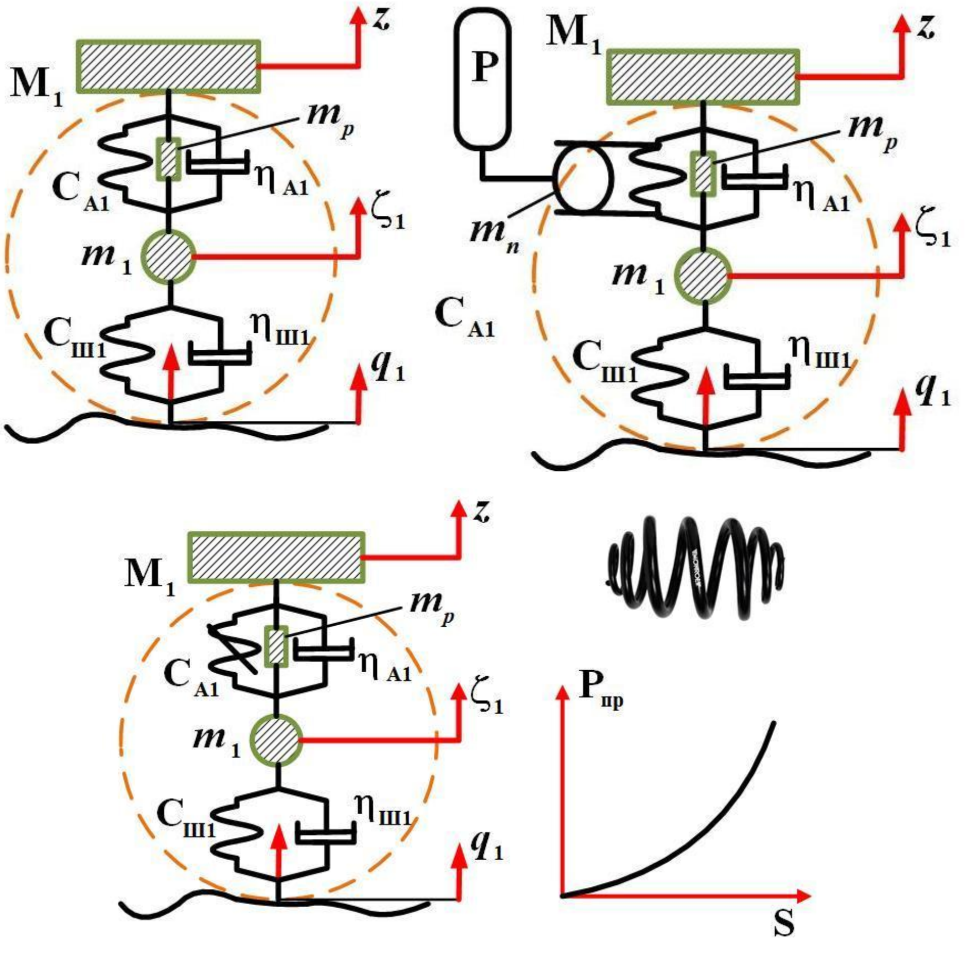


Figure 6 – Model of a Fully Active Suspension System
where: mp – active element of the suspension system.

DISCUSSION OF RESEARCH RESULTS

One possible solution to reduce the body oscillation effect is the use of active suspension systems, which can react to changes in road conditions and compensate for body oscillations, although they do not account for disturbances caused by installed equipment (such as weaponry on military vehicles). Possible solutions include optimizing suspension system parameters or using special materials for suspension elements and reducing body mass.

The oscillation effect remains a relevant research problem for the development of technologies that can minimize its impact on vehicle movement. Further research is needed to study the influence of various factors on vehicle body oscillations and to develop new methods and technologies for their mitigation.

In the development of improved technical solutions for military vehicle suspension elements and the research methods for suspension system processes and states, several problems have been identified. These include the lack of a systematic approach for selecting technical solutions based on mathematical modeling for the synthesis of suspension structures and parameter selection. Current models are often either overly simplified or too complex. Furthermore, analysis and synthesis tasks are not integrated into a generalized parametric framework that should cover both the choice of suspension elements and operating modes, as well as material properties and technical performance requirements.

CONCLUSIONS

An analysis of research methods and models for automotive suspension systems was conducted to identify the advantages and disadvantages of different types of suspensions and classify them as mechatronic systems. Advantages and disadvantages of various suspension types were determined, and a classification was proposed for further modeling and evaluation of operational properties.

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***Пелех О. Р.* Аналіз методів та моделей досліджень систем підресорювання автомобілів**

Конструкція підвіски автомобіля має найбільший вплив на такі його експлуатаційні властивості: плавність ходу, стійкість і керованість. Підвищення плавності ходу забезпечує комфортні санітарні умови на місцях водія та пасажирів. Як правило, висока плавність ходу може бути досягнута зниженням жорсткості пружного пристрою і коефіцієнта демпфірування амортизатора і, відповідно, збільшенням ходу підвіски. Тому важливим є визначенні недоліків різних типів підвісок, їх класифікація і подальше дослідження їх властивостей.

При розробках по вдосконаленню технічних рішень елементів систем підресорювання військових автомобілів та методик дослідження процесів і станів роботи систем підресорювання існує ряд проблем, що потребують вирішення. Це відсутність впорядкованого системного підходу, який всесторонньо описує процес вибору технічних рішень цих елементів на основі формулювання математичних моделей опису процесів і станів для проведення синтезу структури і вибору параметрів. При аналізі встановлено, що наявні математичні моделі процесів і станів деколи є або необґрунтовано спрощеними, або занадто громіздкими.

Проведено аналіз методів та моделей досліджень систем підресорювання автомобілів для визначення переваг та недоліків різних типів підвісок. Проведено аналіз підвісок (двоважільна, багатоважільна, адаптивна, залежна, напівзалежна) за ознаками: простота, компактність, надійність, шумо- і віброізоляція, керованість, можливість встановлення ведучого моста, дешевизна, дешеве обслуговування. Здійснена їх класифікація як мехатронних систем: пасивні системи підвісок, адаптивні системи підвіски, підвісні системи з можливістю швидкого регулювання характеристик демпфера, повільно активні системи підвісок, повністю активні системи підвісок

Визначені переваги та недоліки різних типів підвісок, їх класифікація як мехатронних систем необхідні для послідуючого моделювання роботи і визначення експлуатаційних властивостей.

Ключові слова: підвіски автомобіля, систем підресорювання, мехатронні системи, плавність ходу, моделі досліджень.

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