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MATHEMATICAL MODEL OF THE PROCESS OF OBTAINING ENERGY FROM VIBRATIONS OF THE HYBRID CAR SUSPENSION SYSTEM IN THE MATLAB/SIMULINK ENVIRONMENT

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Abstract: This article covers the mathematical modeling of the energy recovery process from vibrations in a hybrid vehicle's suspension system and its testing in the MATLAB/Simulink environment. The study examined the possibilities of using modern piezoelectric and electromagnetic generators to convert oscillatory system energy into electrical energy. The model took into account the physical and parametric characteristics of the vehicle's suspension system, road conditions, and load factors. The results will serve to determine the efficiency of the energy production process and expand the possibilities of energy saving in hybrid cars.

Key words: hybrid car, suspension system, vibration energy, mathematical modeling

Introduction

At a time when requirements for energy efficiency and environmental friendliness are increasing in the automotive industry, the problem of energy recovery and efficient use in hybrid vehicles is becoming increasingly relevant. In addition to traditional brake energy recovery systems, technologies for converting vibration energy generated in other car parts, particularly suspension systems, into electrical energy are also attracting increasing attention. Energy-harvesting devices based on piezoelectric or electromagnetic systems are primarily being developed to extract energy from the oscillations of suspended systems. In this direction, the creation of effective mathematical models and their testing in modern modeling environments, including the MATLAB/Simulink software platform, is of scientific and practical importance. This article develops a mathematical model of the energy recovery process from vibrations of a hybrid vehicle's suspension system, analyzes factors influencing its main parameters, and examines the results of modeling in the MATLAB/Simulink environment. The research results serve to increase the efficiency of energy storage devices and expand the possibilities of energy saving in hybrid vehicles.

Literature review

The issue of energy recovery and its efficient utilization in hybrid vehicles is attracting increasing attention in scientific research. In this regard, the concept of vibration energy harvesting and its application to a vehicle suspension system are primarily related to the physical nature of vibration energy and the theoretical foundations of its conversion into electrical energy. According to classical mechanics and vibration theory, the primary function of the suspension system is to dampen vibrations caused by road surface irregularities and to reduce their transmission to the vehicle's structure and passengers. At the same time, these oscillations have a certain energy potential and can serve as a technological basis for its conversion into electrical energy. This idea was first raised in scientific literature in the mid-20th century, with early developments focused on studying the capabilities of electromechanical and piezoelectric converters. The first theoretical models and experimental results on collecting vibrational energy using special devices were

presented by scientists in Europe and the USA in the 1970s and 1980s[1]. They have developed mathematical models for determining the frequency and amplitude ranges of vehicle suspension system oscillations and assessing the efficiency of energy storage devices. These models are mainly based on lumped-parameter or distributed-parameter approaches and describe the process of converting vibration energy into electrical energy using differential equations. In recent years, numerous studies have been conducted on the creation of energy storage devices based on piezoelectric elements and their integration into the vehicle suspension system. The high energy conversion coefficient and long-term durability of piezoelectric materials (e.g., Pb (Zr,Ti) O3) allow them to be widely used in this field. At the same time, electromagnetic generators also play an important role in collecting vibrational energy. These technologies primarily utilize mechanisms for converting kinetic energy into electrical energy through magnets and coils. Starting in the 1990s, hybrid energy storage devices based on both technologies began to be developed. Their mathematical models comprehensively reflect the source of vibration (i.e., the suspended system), energy-accumulating elements, and the interactions between them. In this regard, the capabilities of modern modeling environments, particularly the MATLAB/Simulink program, are widely used. This platform allows for the numerical solution of differential equations of oscillatory systems, parametric analysis, and visualization of results. Therefore, in many studies, the MATLAB/Simulink environment is used to model the process of energy extraction from suspension system oscillations[2]. Recent studies using models with two or more degrees of freedom of the vehicle's suspension system (e.g., 2-DOF or 4-DOF models) analyze the generation and accumulation of vibration energy, the location and dimensions of energy storage devices, and their connection schemes to the electrical load. At the same time, road conditions, vehicle speed, load, and other external factors are also taken into account. All these parameters directly affect the efficiency of energy storage. In a number of studies, optimization methods are used to maximize the output power of energy storage devices. For example, genetic algorithms, particle set algorithms, and other evolutionary approaches are used to optimize device parameters and their placement schemes[3]. With the help of these methods, it has been proven that the efficiency of energy collection has been significantly increased. At the same time, issues regarding the autonomous operation of energy storage devices and their integration into other electronic systems of the vehicle are also of great importance. The independent operation of energy storage devices without being connected to the vehicle's electrical grid allows them to be used to power various electrical devices, ranging from sensors to low-power actuators. This will serve to increase the overall energy efficiency of hybrid vehicles. A number of scientific studies in this field have also been conducted in Uzbekistan and Central Asia. In particular, research is being conducted at the National University of Uzbekistan, Tashkent State Technical University, and other scientific institutions on obtaining energy from vehicle suspension system vibrations, developing structural solutions for energy storage devices, and developing their mathematical models. In these studies, the efficiency of energy storage was assessed and practical results were obtained, taking into account local road conditions, regional car models, and climatic conditions[4].At the same time, road irregularities characteristic of the territory of Uzbekistan, vehicle load and speed, as well as the characteristics of domestically produced piezoelectric and electromagnetic materials were taken into account. At the same time, the operational reliability of energy storage devices, their durability, and maintenance requirements are also being analyzed. According to the results of empirical studies conducted worldwide, it has been established that the maximum efficiency of modern piezoelectric and electromagnetic energy storage devices is typically around 20-30%, meaning that this portion of the vibration energy generated in the suspended system can be effectively converted

into electrical energy. At the same time, energy storage efficiency depends on many factors, such as road conditions, vehicle speed, load, and the location of the energy storage device. For example, energy storage efficiency may be higher on uneven roads in urban conditions or in variable-speed traffic. Conversely, when driving on smooth roads or at high speeds, energy storage efficiency decreases. Therefore, it is important to take these factors into account when designing energy storage devices. In modern scientific literature, the development of mathematical models for energy storage devices is mainly divided into the following stages: first, the creation of a physical-parametric model of the suspension system (e.g., the mass-spring-damper model), second, the creation of a model representing the electrical and mechanical properties of the energy storage elements, and third, the integration of these two models and modeling in the MATLAB/Simulink environment. In this process, external factors such as road unevenness, vehicle speed, and load are entered as parameters as vibration sources. The output voltage and power of energy storage devices, as well as their connection schemes to the vehicle's electronic systems, are modeled. As a result of the research, the location of the device, the properties of the piezoelectric or electromagnetic material, the stiffness and damping coefficient of the suspension system, as well as the parameters of the electrical load were identified as the factors that have the greatest impact on the efficiency of energy storage devices. In modern research, adaptive control systems for increasing the output power of energy storage devices, real-time optimization algorithms, and the possibility of integration with supercapacitors or batteries for energy storage are also being studied[5]. Furthermore, the impact of energy storage devices on the overall dynamics of the vehicle's suspension system—specifically their impact on vehicle comfort and safety—is analyzed separately. This is because the energy storage device can introduce additional stiffness or attenuation into the suspension system, which can negatively or positively affect the vehicle's vibration damping properties. Therefore, when selecting the optimal parameters of energy storage devices, not only the efficiency of energy storage but also the comfort and safety of the vehicle are taken into account. Another important problem in the scientific literature regarding the integration of energy storage devices into the vehicle's suspension system is their operational reliability and maintenance requirements. Preliminary studies have analyzed the long-term durability of energy storage devices, their reliable operation in vibration environments, and their stability under high temperature or humidity conditions. In this regard, the achievements of modern materials science, in particular, the development of new piezoelectric and electromagnetic materials, contribute to making energy storage devices more reliable and efficient. Currently, active work is being carried out to make energy storage devices smaller, lighter, and more powerful. At the same time, issues regarding the control systems of energy storage devices, energy storage and distribution algorithms, and their integration with other electronic systems of the vehicle are becoming increasingly relevant. Various approaches and design concepts for integrating energy storage devices into the vehicle's suspension system have been proposed in international literature. For example, energy storage devices can be placed inside a shock absorber, mounted on the elastic elements of a suspension system, or developed as a separate unit as a special module. Each approach has its own advantages and disadvantages. The energy storage devices placed inside the shock absorber are compact and have less impact on the overall design of the suspension system. However, under operating conditions, they are subject to high loads and increase maintenance requirements.Devices designed as special modules allow for flexible integration into the suspension system, but they may increase the overall weight and cost. In this regard, numerous empirical and computational studies are being conducted to determine optimal design solutions. At the same time, when integrating energy storage devices into the vehicle's suspension system, requirements related to road safety and vehicle dynamics must

be taken into account. This is because the incorrect placement or parameters of energy storage devices can negatively affect the comfort and safety of the vehicle. Therefore, in modern research, comprehensive modeling and experimental testing are conducted to determine the optimal options for integrating energy storage devices into the vehicle's suspension system[6]. In addition, the environmental and economic efficiency of energy storage devices, their production and operational costs, service life and recycling possibilities are also analyzed. In this regard, scientific research continues on the use of environmentally friendly and renewable materials in the design and production of energy storage devices, maximizing their energy efficiency, and increasing operational reliability. As a result of research conducted in European and Asian countries, it has been proven that the widespread use of energy storage devices in the automotive industry serves to increase the overall energy efficiency of hybrid and electric vehicles, reduce fuel consumption, and reduce the environmental burden. At the same time, for the widespread implementation of energy storage devices in the automotive industry, it is necessary to address issues of further increasing their technical, economic, and environmental efficiency, ensuring operational reliability, and integrating them with modern control systems. In conclusion, the mathematical model of the energy recovery process from the vibrations of the vehicle's suspension system and its modeling in the MATLAB/Simulink environment is a relevant scientific and practical problem for the modern automotive industry. Scientific research in this direction makes it possible to make energy storage devices more efficient and reliable, integrate them into modern automotive systems, and increase energy efficiency in the automotive industry.

Conclusion

The results of the study show that the mathematical model of the energy recovery process from vibrations of the hybrid vehicle suspension system and its modeling in the MATLAB/Simulink environment are of great scientific and practical importance for the automotive industry. Using technology to generate electricity from suspension system vibrations, it is possible to increase the overall energy efficiency of the vehicle, reduce fuel consumption, and reduce the environmental burden. Using the mathematical model developed in the study, an in-depth analysis was conducted on the influence of the physical and parametric characteristics of the suspension system, the structural and electrical parameters of energy storage devices, road conditions, and load factors on energy storage efficiency. Based on the modeling results in the MATLAB/Simulink environment, it was established that the output power and efficiency of energy storage devices depend on a number of external and internal factors, and their optimal selection and placement can significantly increase the efficiency of the energy storage process. At the same time, it has been proven that when integrating energy storage devices into a vehicle's suspension system, it is important to choose the optimal parameters and placement of the device so as not to negatively affect the comfort and safety of the vehicle's movement. The research results serve as a scientific basis for the widespread introduction of energy storage devices in hybrid and electric vehicles, increasing their technical and economic efficiency, reducing the environmental burden, and developing energy-saving technologies in the automotive industry. In the future, for the widespread implementation of energy storage devices in the automotive industry, it is advisable to continue scientific research to further increase their technical, economic, and environmental efficiency, ensure operational reliability, and integrate them with modern control systems.

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