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ANALYSIS OF CONSTRUCTIVE SOLUTIONS FOR INTELLIGENT SUSPENDED ENERGY COLLECTION SYSTEMS IN HYBRID VEHICLES

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Abstract: This article provides a comprehensive analysis of the structural solutions for smart suspension systems that accumulate energy in hybrid vehicles. Based on modern technologies, the operating principles of suspended systems, methods for increasing their efficiency, and the optimization of energy storage processes are discussed. The literature review examines the theoretical and practical foundations, classical and modern approaches, as well as international and domestic experience. Based on the research results, conclusions are drawn regarding advanced structural solutions and their future application in the transport sector.

Key words: hybrid transport, smart suspension system, energy storage, structural solutions

Introduction

In recent years, ensuring environmental sustainability and reducing energy consumption have become key priorities in the global automotive industry. In this regard, hybrid vehicles are distinguished by their advantages, as they combine traditional engines and electric drives, allowing for reduced fuel consumption and reduced harmful emissions. However, to further increase the efficiency of hybrid vehicles, it is important to collect and reuse energy from secondary sources. In particular, energy-saving smart suspension systems have great potential in this regard, allowing them not only to improve the vehicle's driving comfort but also to convert vibrations generated during movement into useful energy. This article provides an in-depth analysis of the structural solutions of energy-saving smart suspension systems used in hybrid vehicles, their operating principles, opportunities for increasing efficiency, and prospects for technological development. The purpose of the article is to identify advanced constructive solutions through the analysis of modern scientific and practical sources and to develop recommendations for their implementation.

Literature review

Looking at the history of the development of hybrid vehicles, in the early years, the main focus was on the integration of energy sources. Although the first hybrid cars appeared at the beginning of the 20th century, their mass production and widespread distribution on the global market did not occur until the 21st century. The initial theoretical foundations were formed at the intersection points of classical mechanics and electrical transmission, and Newton's and Lagrange's mechanics, the laws of thermodynamics, and the foundations of electromechanics played an important role in this process. Subsequently, as a result of modern scientific research, the possibility of integrating energy storage and processing systems into the design of hybrid vehicles has emerged. Theoretical and practical research on the development of suspended systems is of particular importance. Initially, car suspension systems served only to ensure traffic comfort and mitigate road vibrations. However, since the beginning of the 21st century, the idea has emerged to add energy storage capabilities to suspended systems. In this case, the main structural elements of the suspension systems - shock absorbers, springs, and stabilizers - were supplemented with

electromechanical or piezoelectric generators. This technological approach allowed for the conversion of kinetic energy generated by the vehicle's movement into electrical energy. In this regard, research conducted by G. Smith and his colleagues has theoretically and experimentally substantiated the effectiveness of energy-harvesting suspended systems. Their work demonstrated optimal methods for energy harvesting using electromagnetic generators placed in a suspension system and revealed the significance of this technology for hybrid vehicles.

In terms of theoretical and conceptual foundations, intelligent suspension energy storage systems are an integrated result of the physical, mechanical, and electronic sciences. Modern scientific literature extensively highlights the operating principles of these systems, their control algorithms, and efficiency indicators. For example, in the mathematical models of suspended energy storage systems proposed by C. Williams and D. Yates, the processes of converting kinetic energy into electrical energy through electromechanical generators placed inside shock absorbers are analyzed in detail. These models take into account factors such as the dynamic motion of the system, oscillation frequency, load, and road conditions. Based on these approaches, optimization methods have been developed, and opportunities for increasing energy storage efficiency have been identified[2].

Within the framework of historical classical theories, the primary function of suspension systems was to reduce vehicle body vibrations and ensure comfortable movement for passengers. In this regard, the works of scholars such as K. F. Dunkerley and S. Timoshenko served as a basis. Their research addresses the creation of mechanical models of suspension systems, as well as the calculation and optimization of oscillations. However, the energy storage function began to be implemented only in the modern era, with the development of electrical and electronic technologies. In this regard, traditional spring and shock-absorbing mechanisms in new-generation suspension systems have been supplemented with electromechanical elements. This approach plays an important role in improving the overall efficiency of the vehicle and ensuring energy efficiency. Modern smart suspension systems integrate microprocessor control units, sensors, and actuators that analyze road conditions in real time and automatically control the stiffness and height of the suspension system.

The contribution of regional and national scientists should be particularly noted. Research in the automotive industry in Uzbekistan and Central Asian countries is also of great importance in this direction. In particular, scientific schools at the National University of Uzbekistan and Tashkent State Technical University are conducting research on the technical and technological characteristics of hybrid vehicles and structural modifications of energy storage systems. A number of scientific articles have been published by domestic authors, specifically A. Kholmatov and N. Kadyrov, on the development of mechanical and electromechanical models of energy-harvesting suspension systems and their practical implementation. Their work is primarily aimed at developing domestic modifications of energy storage suspension systems, taking into account the road conditions and climatic characteristics of Uzbekistan. These studies play an important role in adapting international experience and modern technologies to local conditions[3].

In the field of empirical research and practical applications, various structural variants of intelligent suspension energy storage systems have been tested. In particular, suspension systems based on electromagnetic, piezoelectric, and hydraulic generators have been developed, and their efficiency has been evaluated through laboratory and road tests. The main advantage of such systems is the ability to charge batteries and power auxiliary electrical systems by converting vibration and vibration energy generated by vehicle movement into electrical energy. For example, energy-saving suspension systems in hybrid vehicles developed by Toyota and General Motors

have been tested in pilot projects. Test results showed that using such systems, it is possible to collect 50-100 W*h of electricity per 100 km of travel. This allows for an increase in the overall energy efficiency of the vehicle by 3-5%. Additionally, studies conducted in the USA, Japan, and European countries analyzed the efficiency of energy-accumulating suspension systems depending on road conditions, load, and speed, and developed optimal control algorithms[4].

In terms of critical analysis and scientific debates, there are also some limitations and problems of smart suspension energy storage systems. For example, the weight and size of electromechanical generators can increase the overall mass and structural complexity of a vehicle. Furthermore, the efficiency of converting vibration energy into electrical energy is not high—in existing systems, this figure is around 30-40%. Therefore, scientific research continues in the direction of system miniaturization, increasing energy storage efficiency, and reducing production costs. Some scientists argue that efficiency can be increased by replacing electromechanical generators in suspended systems with high-performance piezoelectric materials, using nanocoatings, and implementing intelligent control algorithms. At the same time, energy storage systems must not negatively affect the vehicle's core functions—that is, they must not reduce comfort and safety. In this regard, advanced technological solutions—such as adaptive and proactive suspension systems—deserve primary attention[5].

Modern scientific trends indicate that artificial intelligence, machine learning, and IoT (Internet of Things) technologies are becoming increasingly important in the development and implementation of intelligent suspension systems for energy storage in hybrid vehicles. For example, intelligent control algorithms are being developed to monitor road conditions in real time and adjust the stiffness and energy storage parameters of the suspension system, taking into account traffic speeds and loads. It was found that using such systems can increase the efficiency of energy storage by 10-15%. Furthermore, smart suspension systems ensure vehicle safety, passenger comfort, and energy efficiency at the same time. As a result of joint research by domestic and foreign scientists, new structural options for energy storage suspension systems are being developed, including modular and easily modernizable solutions. This will allow these systems to be adapted and implemented for a wide range of car models in the future[6].

An analysis of the aforementioned literature shows that energy-saving intelligent suspension systems play an important role in the technological development of hybrid vehicles. Their theoretical foundations are based on the achievements of classical mechanics and modern electronics, while applied research is aimed at increasing system efficiency and reducing production costs. Cooperation between local and international scientific schools, along with the use of new materials and control algorithms, is defining the future development prospects of energy-harvesting suspended systems. In particular, increasing the efficiency of energy storage, system miniaturization, and the implementation of intelligent control technologies remain among the most pressing tasks today.

Conclusion

Based on the scientific and practical literature analyzed above, it can be concluded that the structural solutions of energy-saving intelligent suspension systems in hybrid vehicles have been developing rapidly in recent years, and a number of advanced results have been achieved in this direction. Modern technologies, in particular, the development of energy-accumulating suspension systems based on electromechanical, piezoelectric, and hydraulic generators, allow for the conversion of vibration energy generated by vehicle movement into efficient electrical energy. At the same time, the implementation of intelligent control algorithms, microprocessor control systems, and artificial intelligence technologies are being used to optimize energy storage processes. As a

result of scientific research, practical tests, and experiments by domestic and international scientists, structural solutions are being developed to increase the efficiency of energy-saving suspension systems, reduce production costs, and implement them in large-scale hybrid vehicles. However, some limitations of these systems—weight, volume, and energy conversion efficiency—have not yet been fully resolved. Nevertheless, energy-saving intelligent suspension systems are of great importance in the technological innovations of hybrid vehicles, opening up great opportunities for their widespread application in the transport sector in the future. In this regard, the introduction of new materials, advanced control algorithms, and artificial intelligence technologies remains one of the important strategic directions.

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