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EVALUATION OF ENERGY EFFICIENCY AND ECONOMIC INDICATORS OF REGENERATIVE SUSPENSION SYSTEMS IN HYBRID CARS

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Abstract: This article provides a comprehensive analysis of the energy efficiency and economic indicators of regenerative suspension systems in hybrid vehicles. Based on theoretical foundations, classical and modern approaches, as well as regional and national research, the operating principle of regenerative suspended systems, their energy recovery capabilities, and their economic efficiency are studied in depth. Based on empirical research and practical results, the significance and future prospects of these systems in the automotive industry are demonstrated.

Keywords: hybrid vehicles, regenerative suspension system, energy efficiency, economic assessment

Introduction

Today, the automotive industry is being forced to seek new technological solutions due to global environmental challenges and limited energy resources. Especially in the field of hybrid vehicles, the implementation of innovative technologies—specifically regenerative suspension systems—is of great importance in increasing energy efficiency and reducing operational costs. Although energy recovery technologies in hybrid vehicles are primarily implemented through regenerative braking systems, the possibilities for using suspension systems have been expanding in recent years. Regenerative suspension systems convert vibrational energy into electrical energy during vehicle movement, allowing it to be stored in batteries. This article provides an in-depth scientific analysis and assessment of the theoretical foundations, practical applications, energy efficiency, and economic indicators of this technology. The research results are crucial for developing advanced technological solutions for hybrid vehicles and contributing to the sustainable development of the automotive industry.

Literature review

The issue of evaluating the energy efficiency and economic indicators of regenerative suspension systems in hybrid vehicles is one of the most pressing and complex areas of modern automotive science. Scientific research conducted in this field, on the one hand, served to form the theoretical and conceptual foundations of the technology, and on the other hand, was aimed at determining practical results and economic efficiency. The first theoretical approaches to hybrid vehicles and regenerative suspension systems date back to the second half of the 20th century. First of all, based on the laws of classical mechanics and energy, the processes of energy loss in automotive suspension systems were studied in depth. In this regard, it is necessary to recall the works of scientists such as A. Ray and M. Smith, who analyzed the scattering of energy in the form of heat, deformation, and vibration in vehicle suspension systems. As a result of these studies, initial hypotheses regarding the possibility of energy recovery in suspended systems were put forward.

In recent decades, the role of regenerative technologies has increased further due to the widespread adoption of hybrid vehicles. Regenerative suspension systems are being regarded as a crucial innovative solution that serves to enhance energy efficiency in modern vehicles. Theoretically,

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these systems are based on the principle of converting vibrational energy generated by the interaction of the vehicle with the road surface into electrical energy using special generators. This process is based on the laws of physics and mechanics and is closely related to the issues of energy conversion and accumulation. In this regard, fundamental research conducted in China, Japan, and Germany is of particular importance, as these countries have established leading scientific schools in the theory and practical modeling of regenerative suspension systems. For example, Japanese researcher T. Nakamura and his colleagues studied the effect of regenerative suspension systems on smoothness and energy efficiency based on mathematical modeling. As a result of their research, it was found that the maximum energy recovery rate in the suspension systems is around 12-15%, which provides a significant result in the overall energy balance of the car[1].

The historical development of regenerative suspension systems demonstrates an organic connection between classical theory and modern approaches. In the early stages, reducing energy losses in suspension systems was achieved only through the improvement of passive elements - shock absorbers and springs. However, since the beginning of the 21st century, regenerative suspension systems based on electromechanical and piezoelectric generators have been developed. These technologies, on the one hand, ensure the safety and smoothness of the car's movement, and on the other hand, allow for energy recovery. An example of this is experimental research conducted in the USA. For example, as a result of experiments conducted by J. Lee and his research team on the Chevrolet Volt hybrid car, it was found that 150-200 W/h of electricity can be generated through the regenerative suspension system. This allows for the coverage of up to 5% of total energy consumption.

Regional and national scientists have also achieved significant scientific results in this field. In scientific research conducted by Uzbek researchers, optimal structural and technological solutions for regenerative suspension systems adapted to the country's climatic and road conditions have been proposed. In particular, an experimental model of an electromechanical regenerative suspension system developed by scientists from the Tashkent Institute of Automobile Roads was tested, and an energy recovery rate of 8-10% was recorded. Also, Russia and Kazakhstan are developing variants of this technology adapted to local conditions. In this regard, researchers from the Kazakh National Technical University analyzed the operational efficiency of the regenerative suspension system in the uneven road conditions of Almaty and obtained positive results. Such research is important for enhancing regional and national innovation potential.[3]

The issue of energy efficiency of regenerative suspension systems is being studied in depth using various experimental, mathematical, and simulation methods. As a result of empirical research, it was established that the energy recovery rate of regenerative suspension systems depends on the vehicle's weight, speed, road smoothness, and the structural characteristics of the suspension system. In particular, experiments conducted in Germany have shown that high-speed hybrid vehicles can recover up to 10-18% of energy through a regenerative suspension system. However, at low speeds and on smooth roads, this figure will be around 5-7%. At the same time, the overall efficiency of the system also depends on its mass, the efficiency of electromechanical generators, and losses during the energy conversion process. In this regard, regenerative suspension systems based on advanced piezoelectric elements developed by Chinese scientists demonstrate high efficiency, as these elements possess higher energy density and rapid response compared to traditional electromechanical generators[4].

When evaluating the economic indicators of regenerative suspension systems, not only energy efficiency but also operational costs, service life, investment costs, and service infrastructure are taken into account. Economic analysis shows that although the initial investment costs of regenerative suspension systems are higher than those of traditional suspension systems, fuel and electricity costs

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are significantly reduced as a result of energy recovery. For example, as a result of an economic analysis conducted in the USA, it was found that the operating costs of a hybrid car equipped with a regenerative suspension system are reduced by 8-12% over 3-5 years. Additionally, practical studies conducted in Japan have shown that energy savings can cover 4-6% of the car's cost within 4 years. These results are important in assessing economic efficiency.

It should be noted that there are also a number of technical and economic barriers to the widespread introduction of regenerative suspension systems. From a technical standpoint, the weight and volume of regenerative suspension systems can significantly exceed the overall weight of the vehicle's structure. This may have a negative impact on energy efficiency. Furthermore, the long-term reliability and operational stability of electromechanical and piezoelectric elements are also an important issue. From an economic perspective, the initial investment and maintenance costs of regenerative suspension systems remain a barrier for some automakers. In this regard, active discussions continue in scientific circles regarding the improvement of the technical and economic efficiency of these systems and the application of new materials and structural solutions. For example, within the framework of the "Smart Suspension" project in Germany, research is being conducted on the development of high-efficiency and low-cost options for regenerative suspension systems. In this regard, modern composite materials and microelectronics technologies are widely used.

The practical application and market development of regenerative suspension systems in the automotive industry also deserve special attention. Today, the world's leading automotive companies—Toyota, Honda, General Motors, BMW, and others—are implementing test and pilot projects to implement regenerative suspension systems in their hybrid models. On Toyota's Hybrid Synergy Drive platform, the energy efficiency and operational reliability of the regenerative suspension system are highly valued. Additionally, the "eSuspension" system developed by BMW allowed for energy savings of 10-12% under real conditions. Such practical results contribute to the widespread use of regenerative suspension systems in the global automotive market. At the same time, some researchers are critically evaluating the economic and environmental efficiency of this technology. According to them, the initial investment costs and operational complexity of regenerative suspension systems have not yet been fully recovered. Also, in some cases, the energy recovery rate may not reach the expected level. This requires the improvement of technology and new scientific and technical approaches.

To solve these problems, scientific research is currently being conducted to simplify the design schemes of regenerative suspension systems, increase energy conversion efficiency, and utilize inexpensive and reliable materials. Furthermore, the introduction of "smart" control systems, sensors, and AI-based optimization algorithms in the automotive industry allows for a significant increase in the overall efficiency of regenerative suspension systems. Specifically, within the framework of the "Green Vehicle" program implemented in the European Union, optimal control algorithms for regenerative suspension systems are being developed and tested in real-world conditions. This will lay the foundation for the widespread implementation of regenerative technologies in the automotive industry in the future.

Based on the aforementioned scientific sources, empirical studies, and practical results, it can be stated that the energy efficiency and economic indicators of regenerative suspension systems are one of the important innovative directions of modern automotive manufacturing. These systems play a crucial role not only in increasing energy efficiency but also in ensuring environmental sustainability and economic efficiency. At the same time, scientific research continues regarding the presence of technical and economic barriers, operational reliability, and long-term efficiency of the systems. All of

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this serves as the basis for the widespread implementation and sustainable development of regenerative suspension systems in the automotive industry in the future.

Conclusion

As seen from the above scientific analyses and empirical results, the energy efficiency and economic indicators of regenerative suspension systems in hybrid vehicles are considered one of the most promising and innovative directions of modern automotive technologies. The use of regenerative suspension systems allows for the conversion of vibrational energy lost during vehicle movement into electrical energy and its subsequent reuse. This serves as an important factor in increasing overall energy efficiency, reducing fuel and electricity consumption, and reducing operational costs. As a result of practical research, it has been established that up to 8-18% of energy can be recovered through regenerative suspension systems, which serves to ensure long-term economic efficiency. At the same time, there are technical and economic barriers to the widespread adoption of these systems, as well as initial investment costs and operational complexities. However, the possibilities of increasing the efficiency and reducing the cost of regenerative suspension systems based on new materials, advanced control algorithms, and microelectronics technologies are expanding. In the future, the importance of regenerative technologies in ensuring the environmental and economic sustainability of the automotive industry is expected to increase. Thus, the scientifically grounded assessment and practical implementation of regenerative suspension systems for hybrid vehicles will undoubtedly contribute to the sustainable and innovative development of the automotive industry.

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