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A review of brake energy recovery systems and vibration energy recovery systems in new energy vehicles

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Abstract:
As the automotive industry faces the dual challenges of energy crisis and environmental degradation, developing new energy vehicles (NEVs) has become a focal point. This paper presents a comprehensive overview of braking and vibration energy recovery systems in NEVs. Specifically, it explores these systems' theoretical foundations, control strategies, and current research status. The braking energy recovery system aims to enhance energy efficiency by capturing and reusing the energy generated during braking. In contrast, the vibration energy recovery system seeks to expand energy recovery channels by absorbing vehicle vibrations. While considerable research has been conducted on braking energy recovery, there is still a need for further exploration in vibration energy recovery. By optimizing these systems, we aim to contribute to the sustainable growth of the NEV industry, ultimately benefiting both the environment and energy conservation efforts.

Keywords: braking energy recovery, braking force distribution, control strategy, influencing factors

1. Introduction

1.1 Research background

Amidst the growing concerns of environmental pollution and energy crisis, developing new energy vehicles has emerged as a crucial aspect of sustainable transportation. This paper aims to comprehensively investigate the methods of reducing energy loss in new energy vehicles, focusing on the braking and vibration components. This research domain's current status and future trends are explored, highlighting its significance in academic research and practical applications. The objective is to identify the optimal energy recovery methods by simulating and comparing various strategies. The innovation lies in the integrated analysis of braking and vibration systems, offering a novel perspective on energy-efficient vehicle design.

1.2 Classification and Overview of New Energy Vehicles

New Energy Vehicles (NEVs) have advanced technological principles and structures that use conventional automotive fuels and new on-board power units combined with automotive power control and drive technologies.
New energy vehicles are roughly categorized as follows: Hybrid Electric Vehicles (HEVs), fuel-efficient vehicles equipped with an electric motor. On top of the traditional engine, this type of vehicle is equipped with an electric drive system that allows for hybrid drive. Pure electric vehicles (BEVs), including solar-powered vehicles), as the name suggests, are vehicles that are powered entirely by electric energy. Fuel Cell Electric Vehicles (FCEV) are automobiles that rely on electric motors to drive them, using hydrogen, methanol, etc., as fuel and generating an electric current through a chemical reaction.[1].

1.2.1 all-electric vehicle

A pure electric vehicle (BEV) is a vehicle that uses on-board power as a power source and provides the driving force for the car through motor-driven wheel rotation.
It is an automobile that complies with safety regulations, road traffic, and other requirements. Pure electric vehicles usually use a single high-efficiency rechargeable battery as the power source for energy storage.

1.2.2 hybrid car

A Hybrid Electric Vehicle (HEV) is a vehicle that, under certain operating conditions, can obtain drive energy from two or more energy stores, energy sources, or energy converters, and the drive system can consist of two or more individual drive systems that can operate simultaneously.

1.2.3 Fuel Cell Electric Vehicles

Fuel Cell Electric Vehicle (FCEV) uses an electrochemical reaction in the fuel cell to generate electrical energy to drive the vehicle. The difference between a Fuel Cell Electric Vehicle (FCEV) FCEV and an ordinary pure electric vehicle is the difference in the working principle of the power battery, which converts the chemical energy in the battery into electric energy to drive the vehicle through electrochemical reactions.

2. Theoretical study of regenerative braking energy recovery in automobiles

2.1 Current status of domestic and international research on brake energy recovery systems

2.1.1 Current status of foreign research

The so-called braking energy recovery is the process of automobile braking deceleration or stopping, under the premise of ensuring braking safety, part of the car's kinetic energy into other forms of energy storage in the slowdown of braking at the same time to achieve the purpose of energy recovery.

Afterward, the stored energy is released when the car accelerates or goes uphill and used as an auxiliary energy to drive the vehicle forward.

The brake energy recovery system for electric vehicles consists of a regenerative braking part of the electric motor and a conventional hydraulic friction braking part, which can be regarded as an integrated electromechanical system.

It can be regarded as an electromechanical composite braking system. The regenerative braking of electric vehicles is realized using the motor/generator reversibility principle of electric motors[3].

When braking and decelerating, the control circuit that drives the motor to generate electricity starts to work so that the energy of braking and decelerating is converted into the current that recharges the battery and carries out electric braking.

When the brake decelerates, the control circuit that generates power from the motor starts to operate, converting the energy from the brake deceleration into the current for charging the battery, storing the power, and thus regenerating it. The friction hydraulic brake adopts a double-circuit hydraulic brake system to

ensure the safety of braking. Regenerative braking of electric vehicles should meet the following requirements: (1) Reasonable distribution of braking force of front and rear wheels to ensure the stability of braking; (2) Reasonable distribution of mechanical braking force and regenerative braking force, and apply regenerative braking as much as possible under the circumstance of ensuring braking safety.

(3) Rational distribution of mechanical braking force and regenerative braking force to ensure braking safety, apply regenerative braking as much as possible to provide more recovery of energy to enhance the range of the vehicle;

(4) The control strategy should be integrated with ABS, ESP, and other systems without affecting the performance of the original system.

In the braking process, the brake controller determines the braking intensity the driver wants to achieve according to the opening degree of the brake pedal (the actual master cylinder pressure).

The brake controller determines the braking intensity that the driver wants to achieve based on the opening of the brake pedal (the actual master cylinder pressure), determines the braking force of the front and rear axles, and the distribution of friction braking and regenerative braking. The hydraulic system determines the friction brake distribution between the front and rear axles.

Several influencing factors, such as braking intensity, real-time speed, etc, determine the distribution of friction and regenerative braking. The hydraulic system also determines the distribution of friction and regenerative braking.

Several influencing factors, such as brake strength, real-time vehicle speed, etc., determine friction braking and regenerative braking distribution.

Due to the superior characteristics of the brake energy recovery system, it can simultaneously solve the problems of low energy utilization efficiency and environmental pollution of new energy vehicles.

Due to the superior characteristics of the brake energy recovery system, it can simultaneously solve the problems of low energy utilization efficiency and environmental pollution of new energy vehicles, and the development prospect is widely favored.

Many universities, enterprises, and research organizations at home and abroad have researched the brake energy recovery system.

2.1.2 Status of domestic research

China's research on regenerative braking energy recovery is relatively late; the current level of technology still needs to be revised in the early stages of research[4].

The research focuses mainly on the theoretical aspects of brake energy recovery. However, as China's economic level and scientific research capability increase, the energy crisis and environmental problems are becoming more and more serious.

However, as China's economic level and scientific research capacity increase, the energy crisis and environmental problems are becoming more and more serious; the state has strengthened its attention to energy saving and environmental protection and has increased its support for the research of new energy vehicles, and has made significant progress.

Research on new energy vehicles has been supported and has made remarkable achievements.

Some colleges and universities have researched brake energy regeneration system organizations and proposed different proposals. Wang Qingnian of Jilin University has chosen a new type of brake energy regeneration system for

The simulation results show that this control strategy recovers more energy than the parallel control strategy for electric vehicles. Sun Zechang of Tongji University added a hydraulic control unit to the traditional hydraulic braking system of electric vehicles.

Sun Zechang of Tongji University added a hydraulic control unit and pedal displacement sensor on the basis of a traditional hydraulic braking system for electric vehicles, adopted a hardware-in-the-loop method, and conducted experiments on fuel cell vehicles.

The experimental results show that the regenerative and friction braking forces can be well coordinated and controlled, but the energy recovery effect could be better at low speeds.

Universities mainly focus on the control strategy of braking energy recovery and simulate and analyze the recovery efficiency and braking safety effects of different control schemes.

Simulation and analysis of different control schemes' recovery efficiency and braking safety effects have been conducted. Danhong Zhang of the Wuhan University of Technology designed a fuzzy control strategy based on the maximum regenerative braking torque of the motor.

Zhang Danhong of the Wuhan University of Technology designed a fuzzy control strategy based on the maximum regenerative braking torque of the electric motor. Still, it was necessary to consider the driving speed of the car and maximize the electric braking performance of the HEV.

However, the driving speed was not considered, which did not maximize the electric braking performance of HEVs [.

Wu Puxing et al. from Lanzhou Jiaotong University proposed a fuzzy control strategy by considering the driving speed, braking force distribution, and battery characteristics.

Wu Puxing of Lanzhou Jiaotong University proposed a fuzzy control strategy to maximize the regenerative braking performance of HEVs by considering the driving speed, braking force distribution, and battery characteristics, and simulations were carried out.

The results show that this control strategy can recover more braking energy than the original control strategy of ADVISOR software.

The rear braking force is distributed according to the ideal braking force curve, and the friction force and regenerative braking force are distributed according to a specific ratio. In contrast, the total braking force does not exceed the ECE method.

The total braking force does not exceed the ECE regulation's boundary line, and this scheme's control strategy is simple.

Gao Lijie et al. proposed control strategies for different braking strengths. They simulated them in MATLAB and concluded that efficient energy recovery can be realized in low and medium braking strengths.

It is concluded that efficient energy recovery can be realized in low and medium-intensity braking. Zhao Han et al. from Hefei University of Technology designed an automobile braking strategy based on the wheel slip rate. They passed the actual NEDC test with a high recovery efficiency.

The test shows a high recovery efficiency, and the driver has a good braking feeling. Du Jihong from Tsinghua University has designed a braking strategy based on the wheel slip rate.

Model and braking energy recovery constraints: Du Jihong of Tsinghua University proposed a braking energy recovery control algorithm based on a nonlinear planning model and conducted a simulation of it.

Simulink proposes and simulates a braking energy recovery control algorithm based on a nonlinear planning model. Anping Hu from Jilin University applied AMESim and MATLAB [5]software to perform joint simulations and verified the proposed control algorithm.

The joint simulation of AMESim and MATLAB software verifies that the proposed control strategy can effectively improve energy recovery efficiency while ensuring braking stability.

The braking strength has the most significant influence on the recovery efficiency, followed by the road surface adhesion coefficient, and the initial speed has the most minor influence. Zhao Wenping and Lv Fengyang of Jilin University compared the regenerative braking system of buses with the hydraulic braking system.

The two researchers from Jilin University proposed their control strategy for the coordinated control of a regenerative braking system with hydraulic brake and pneumatic brake, and they designed a new type of vacuum booster.

2.2 Research methodology and perspectives

Foreign countries started researching regenerative braking energy recovery systems for automobiles very early. Now, there have been decades of experience accumulation, the critical technology is leading compared to the domestic; braking energy recovery has also become a new technology applied in electric vehicles is more mature, and its research direction is mainly focused on the following points:

(1) Establishment and simulation analysis of vehicle model in the process of brake energy recovery;

(2) Coordinated control of mechanical and regenerative braking and the problem of perfect integrability with the original ABS;

(3) Energy conversion, storage, and coordination between the electric motor and CVT (Continuously Variable Transmission).

In addition to many in-depth theoretical studies abroad, some technologies have been applied in actual vehicles. Yimin Gao et al. Simulation experiments were carried out for different braking intensities. Yimin Gao and Mehrdad Ehsani proposed an ABS for pure and hybrid electric vehicles based on the braking energy recovery system. Yimin Gao and Mehrdad Ehsani proposed a control strategy for the ABS for electric and hybrid cars based on a braking energy recovery system, and the regenerative braking system is compatible with the ABS through the precise design of the power threshold value of the electric motor system. Wicks et al. established a mathematical model for city buses under an urban driving cycle to study the energy-saving effect of the regenerative braking system. Hongwei Gao et al. from Texas A&M University proposed a neural network control system based on switched reluctance motor regenerative braking for hybrid vehicles and analyzed the energy recovery efficiency under cyclic driving conditions.

Panagiotidis et al. established a regenerative braking model for a parallel hybrid vehicle and then simulated the effect of regenerative braking and analyzed and compared the influencing factors. Hoon Yeo used the I-curve as the front and rear brake power distribution strategy. Still, this distribution strategy increases the rear brake power and motor power, which reduces the energy recovery rate and increases the possibility of front or rear wheel locking. Shuiwen Shen of Eindhoven University in the Netherlands conducted a simulation study on flywheel energy storage CVTs. Sungkyunkwan University in South Korea studied the regenerative braking strategy of four-wheel drive HEVs. It proposed a fuzzy control braking control strategy based on it. It conducted simulation experiments to realize the coordinated control of regenerative and mechanical braking of four-wheel drive HEVs[7]. Overseas automobile companies have also extensively researched brake energy recovery systems, some of which have already been applied in vehicles. Toyota Japan launched the EHB program based on the design of an integrated brake energy recovery function brake ABS, which has been applied to the Prius car, effectively improving its energy efficiency and fuel economy. Ford used Continental's brake energy recovery technology in its SUV Escape and received good results. Honda Motor Company developed the INSIGHT hybrid car on the application of a dual-brake force distribution coefficient control regenerative braking system, through which the system can realize the efficient recovery of braking energy of hybrid electric vehicles; the company launched in 1997 with energy feedback braking system EV PLUS electric vehicles, experiments have shown that in the UDDS conditions of the energy, consumption rate has dropped significantly. BMW's BMWX6ActiveHybrid uses full hybrid braking energy recovery technology. When the car travels at low speeds, electric motors mainly drive it, the engine is in a highly efficient working state, and the regenerative braking system is utilized to recharge the batteries to extend the driving range[8].

In summary, some foreign automotive research institutions and manufacturers have successfully applied braking energy recovery technology to their main models and have achieved stage-by-stage success. Still, the current control strategy of braking energy recovery effect could be more precise, and energy recovery efficiency is low. Therefore, with the increase in energy-saving and environmental protection indexes of electric vehicles, more in-depth research should inevitably be carried out.

3 Theoretical study of automotive vibration energy recovery

3.1 Current status of research on vibration energy recovery systems

3.1.1 Current status of research on vibration energy recovery methods

In recent years, the field of energy recovery has received more and more attention from domestic and foreign research. Based on analyzing the operability and energy-saving cycle of vibration energy recovery when the vehicle passes through the highway speed bumps, we propose the relevant vibration energy recovery technology and analyze the characteristics of different vibration energy recovery technologies. Existing energy collection technologies mainly include four methods: electromagnetic collection, hydraulic collection,mechanical collection, and piezoelectric collection[17].

(1) Power generation by electromagnetic action

Wang, Pourghodrat, et al. designed an electromagnetic vibration energy harvesting device for an orbit, where the vertical displacement of the orbit vibration is transmitted to a generator through a rack and pinion. In the figure below, a rack and pinion, a small clutch, etc., keep the generator rotating in a fixed direction. However, similar rack and pinion electromagnetic conversion devices need help with structural accuracy and size installation.

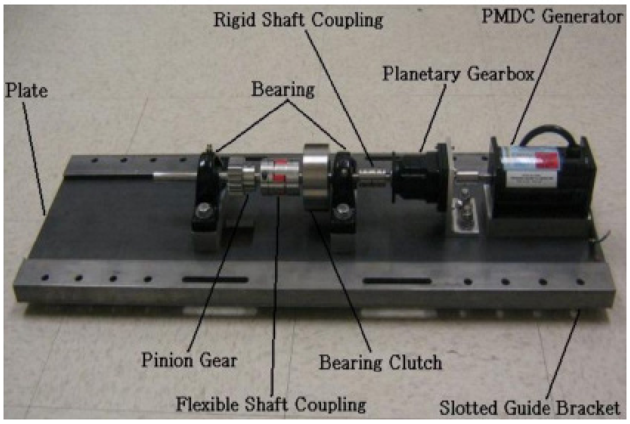

Figure 1. Power generation[Owner-draw].

(2) Power generation utilizing liquid as an energy transfer medium

By utilizing several water-storing rubber belts placed on the highway and covered with metal plates slightly above ground level, the excitation load brought about by the passage of a vehicle rapidly squeezes out the water, which drives a generator that generates electricity. Initial tests have shown that a 1-ton vehicle can generate 1.5 kWh of electricity in a single pass. This way is highly efficient but more complex and not easy to recycle.

(3) Installation of mechanical devices on the road surface for power generation

They are setting up a movable mat on the road surface, placing a kind of inductive mechanism inside, using the gravity effect of the vehicle driving through to make the embedded plate under the road surface similar to the generator like up and down activities, and constantly converting mechanical energy into electric energy. This power generation device will not affect vehicle driving; 10 knots can be comparable to a wind turbine generator. In London, England, as early as 2009, it was proposed to utilize the energy generated when cars pass through the road arch to generate electricity, using the kinetic energy generated by the vehicles to drive the underground gears to create mechanical energy.

(4)Power Generation through Positive Piezoelectric Effect.

Israel has implanted a large number of piezoelectric crystals in the asphalt of ordinary road surfaces, as shown in the figure below, and when vehicles pass through, the entire pavement beam structure vibrates, and the positive piezoelectric effect converts the vibration into electricity, generating about 250 kW of electricity per kilometer. This power generation method has a high energy conversion rate, and some researchers experimentally predict that these piezoelectric crystals implanted in asphalt can be used for at least 30 years.

3.1.2 Current status of coupled vehicle-speed bump vibration theory research

Research on speed bump vibration energy recovery is based on the study of speed bump vibration; the current vehicle-road coupling vibration research has developed a set of a complete theoretical system, such as Shijiazhuang Railway University Professor Yang Shaopu Professor of vehicle-road coupling system dynamics research, in the analysis of the vehicle system modeling and road dynamics analysis under the vehicle respectively, for the coupled system is analyzed, and the test section is established. The literature studies the basic theory and model derivation of vehicle-road coupling and simplifies its computational complexity based on satisfying the primary research. However, its research does not include the problem of modeling the coupling of energy harvesting structures and speed bumps, mainly because of the need for an equivalent assumption method that can characterize the vibration properties of the system. In this paper, we seek a comparable method that can reasonably describe the topological features and vibration mechanical properties of different piezoelectric vibrators, unify the piezoelectric vibrator model with the vehicle-speed bump model after the equivalence, and analyze the dynamics of the coupled system under the coupling mode of different speed bump structures, different road irregularities, different vehicle types and speeds, as well as the coupling mode between the piezoelectric vibrator structure and the speed bump. The vertical vibration displacement response and load response of the piezoelectric vibrator under different speed bump structures, different road smoothness, different vehicle types, different vehicle speeds, and different coupling modes between the piezoelectric vibrator structure and the speed bump are studied as inputs to the piezoelectric vibrator output external characteristic model[18].

3.1.3 Current status of research on vibration energy recovery devices for speed reducer belts

(1) The linear motor structure was designed using the CI (Computational Intelligence) technique, and the design was optimized by GSO calculation. Preliminary bench tests have shown that a 10-meter-long power module installed at an intersection with 8000 vehicles per day can recover 100 MWh of power in a year.

Figure2 linear motor structure [BaiDu engine].

(2) Piezoelectric

In 2013, Craig D designed a piezoelectric device for recovering energy from road vibrations, as shown below. The principle of recovery is that when a vehicle drives over the road surface, the road surface vibrates, the mass block of the device vibrates with it, and it converts the vibration of the road surface as much as possible into electrical energy through the piezoelectric effect of the device. A particular reptile-like image of the piezoelectric material for higher vibration energy characterizes the invention. A single module can generate about 40 Joules of energy through a car [19].

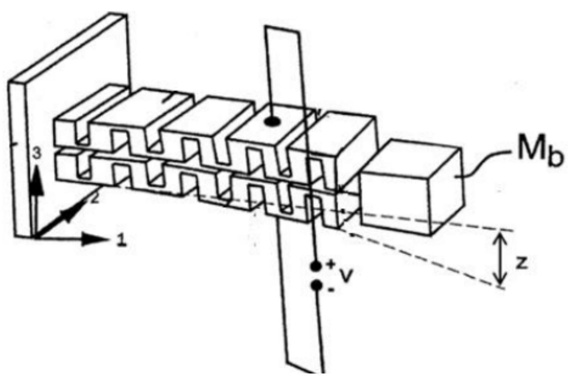

Figure3. piezoelectric[Owner-draw].

(3) Hydraulic

Chen-Ching Ting et al. designed a hydraulic device[21]. When a car drives through the device, the piston moves downward under the action of the wheels, and the oil in the oil chamber flows out of the check valve under pressure into the accumulator, which drives the power generator to generate electricity. The efficiency of the device was calculated to be 40%.

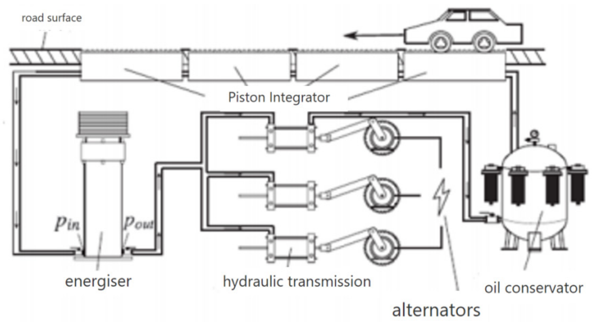

Figure4 Hydraulic[Owner-draw].

Domestic research on vibration energy recovery devices for road speed bumps is in the initial stage, with more discussions on the structure and principles.

There is more research on the structure and principle but less on the design method and the construction of the test bench [22].

4. summaries

In this study, we have comprehensively reviewed the current status of energy recovery systems in new energy vehicles, emphasizing braking and vibration components. We have found that while significant progress has been made in improving energy efficiency, there are still opportunities for further optimization. Future research should focus on developing innovative materials and technologies to enhance the performance and durability of energy recovery systems. Additionally, it is crucial to consider integrating these systems with advanced control algorithms to maximize energy recovery and minimize losses. Furthermore, it is essential to evaluate these systems' economic and environmental impacts to ensure their widespread adoption and sustainability. Overall, the continued research and development of energy recovery systems in new energy vehicles holds great promise for enhancing energy efficiency and promoting sustainable transportation.

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