FRICTION HEAT ENERGY RECOVERY SYSTEM BASED ON HYDRAULIC BRAKE SYSTEM BY WIRE OF HEAVY VEHICLE

by

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Original scientific paper
https://doi.org/10.2298/TSCI2302159G

In order to reduce fuel consumption and environmental pollution, the author proposes a friction heat recovery system based on the hydraulic brake by wire system of heavy-duty vehicles, the system uses the heat energy generated by friction generate electricity, and stores the electric energy in the vehicle battery. This can provide power for the lighting equipment on the vehicle. The experimental results show that after using the recovery system, the braking energy consumption is reduced, and the fuel consumption is 10% less than before, which fully demonstrates the effectiveness of the recovery system for energy conservation, and proves that the heat energy recovery system can effectively reduce fuel consumption and reduce environmental pollution.

Key words: *heavy vehicle, hydraulic brake system by wire, friction heat energy, recovery system, environmental pollution*

Introduction

The excessive consumption of energy has led to sharp changes in the global climate, the greenhouse effect and other issues becoming increasingly prominent, and severe weather such as smog has become increasingly serious in recent years. *Energy conservation and emission reduction* has gradually become a hot topic. Compared with traditional fuel vehicles, new energy vehicles have the advantages of high efficiency, low emissions, low noise*, etc.* In addition, motor braking can also be used to achieve energy recovery and reuse during braking, effectively improving the efficiency of energy use. Nowadays, the superiority of new energy vehicles has been paid more and more attention, and the world is constantly increasing the development and support of new energy vehicle technology. In 2012, after discussion and analysis, the central state council formulated the development plan for energy saving and new energy automobile industry (2012-2020), which requires accelerating the incubation and promotion of energy saving and emission reduction and new energy automobile industry. It is of great significance to mitigate the energy and environmental crisis, promote the transformation and upgrading of the automobile industry, and cultivate new economic growth points [1].

With the development of automotive technology, especially active safety technology, engineers also put forward higher requirements for vehicle dynamics control system. Traditional automobile chassis and electronic control structure do not have active control function, and its chassis structure is mainly composed of mechanical and hydraulic parts, lacking flexibility,

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which makes it difficult to cope with complex and changeable driving conditions and different driving objectives. However, due to the strong coupling characteristics of the dynamics caused by the mechanical/hydraulic connection, there is interference or restriction between different control systems, which makes the energy recovery efficiency of the vehicle under regenerative braking conditions not very ideal [2].

According to the requirements of the sub project development of electric vehicle chassis dynamics control system in the field of modern transportation technology of the National 863 Plan, namely the research and development of prototype electric vehicles with a new generation of chassis controlled by wire and its key technologies, including the research and development of electric power steering system of electric vehicles, the research and development of electric vehicle hydraulic brake system controlled by wire research on key technologies of drive control system based on four-wheel hub motor, and research and development of electric vehicle battery pack and battery management system. Jilin University, as the main participating unit, aims to solve the research and development of a new generation of hydraulic brake system by wire and the key technical problems related to vehicle dynamics matching and control.

With the continuous development of automotive electronic technology, such automotive active safety technologies as ABS, electronic brake force distribution, traction control system (TCS) and electronic stability control have gradually matured and been widely used, therefore, the structure of automobile braking system is becoming more and more complex and bloated, the traditional hydraulic braking system with mechanical direct connection can no longer meet the requirements of modern automobiles for the integration and lightweight of braking system, however, wire signal connection is widely used in wire controlled dynamic system, which is highly integrated and simple in structure, so it can better adapt to the development trend of integrated and lightweight braking system.

Nowadays, people pay more and more attention the problem of environmental pollution, and the exhaust emission of traditional internal combustion engine vehicles is the main source of urban pollution. Due to the zero emission of pure electric vehicles, the electrification of vehicles has become an inevitable trend of the development of the automobile industry. On the one hand, the pure electric vehicle uses the motor as the engine rather than the internal combustion engine. Because the traditional braking system uses the vacuum degree of the engine intake manifold to provide power for the braking system, the traditional braking system can no longer adapt to the pure electric vehicle. On the other hand, the electric vehicle requires the brake system to co-operate with the drive motor and power battery to realize the brake energy recovery, and the traditional hydraulic brake system directly connected by machinery can do nothing about this [3].

Obviously, the traditional hydraulic braking system has been unable to adapt to electric vehicles, and the wire control system can overcome these shortcomings. Therefore, in order to realize the electrification of vehicles, the wire control braking system is an inevitable choice. With the continuous development of science and technology, intelligence has become an inevitable trend in the development of the automobile industry. Intelligent vehicles require the combination of braking system and advanced driver assistance system to achieve intelligent driving functions such as adaptive cruise, automatic emergency braking.

These functions require that the braking system can achieve active braking without driver intervention, while the traditional hydraulic braking system with mechanical connection must be operated by the driver to achieve deceleration braking. Therefore, the traditional hydraulic braking system has been unable to meet the requirements of intelligent vehicles, and a large number of wire connected brake by wire systems can perfectly adapt to intelligent vehicles, only through ECU, you can send braking commands to the braking system instead of the driver, therefore, in order to realize the intellectualization of cars, the brake by wire system is an inevitable choice. To sum up, with the continuous development of the integration and lightweight of the braking system, the electrification and intelligence of the automobile, the brake by wire system will become the mainstream choice of the automobile braking system in the future.

With the rapid development of the automobile industry, high power and large displacement engines are emerging one after another, and vehicle fuel consumption is rising, energy conservation and emission reduction are increasingly valued in engine design. At present, engine heat recovery technologies mainly include exhaust gas turbocharging, subsequent power cycle work, waste heat temperature difference power generation, waste heat refrigeration or heating*, etc.* The author introduces a friction heat recovery system based on the hydraulic brake by wire system of heavy-duty vehicles, which has certain practical significance for energy conservation and environmental protection [4].

Literature review

In simple terms, the wire control technology is to use wires and cables to connect the controller and the actuator, and to cancel the existing technical method of mechanical connection. Nowadays, the control by wire system is relatively widely used in the fields of national defense and aviation, and has also been studied in the field of automotive engineering. The electronic accelerator technology of the engine is an example of the control by wire system. At the 2004 World Automotive Engineer Symposium, people put forward the design concept that the future automobile will be a four wheel and one processor system based on the development prospect of the automobile by wire system. The brake by wire system, which combines the control by wire technology with the automobile brake system, has replaced the traditional hydraulic or pneumatic brake actuators with electro-hydraulic integrated components. It has the characteristics of high control accuracy, fast response speed, easy integration with other control functions, and greatly improves the safety performance of the vehicle during braking. It has a good development prospect and broad market. At present, the brake by wire system is divided into two types. One is the brake by wire system that requires brake fluid as the pressure transmission medium, namely, the electro-hydraulic brake (EHB) system, and the other is a purely mechanical and electronic system. The brake by wire system without brake fluid participation, namely, the electro-mechanical brake system [5].

In 1993, Ford Motor Company and General Motors Company in the USA began to apply the hydraulic brake system by wire (EHB). During this period, the most representative was the *Brake 2000* project launched by Bosch Automotive Parts Company. In 1996, Bosch Auto Parts Co., Ltd. developed a new generation of hydraulic brake system by wire, and carried out a real vehicle test. In 1997, Japan's Toyota Motor Company released the world's first mass production hybrid electric vehicle, Prius, and introduced a new type of brake by wire system (EHB) that can be applied to the brake energy recovery system. Since 2000, the hydraulic brake system by wire has stepped into a mature stage, and has transitioned to a mass production stage. Many companies have commercialized it. In 2001, the new generation of Mercedes Benz SL500 sports car made its debut at the Frankfurt Auto Show. The car was equipped with the SBC (Sensotronic Brake Control) system of Bosch Auto Parts Co., which is a new type of hydraulic brake technology by wire integrated with the electronic Control system and the EHB booster, and was installed on the E – Class 4 matic model of Mercedes Benz in 2003. In 2002, South Korea's Wandu Auto Parts Company developed a new generation of hydraulic regulating unit for the hydraulic brake by wire system. In the same year, at the Frankfurt Auto Show, General Motors of the United States showed the Hy Drive fuel cell concept car, which uses the X Drive electronic control by wire system developed by SKF of Sweden. In 2005, Bosch Auto Parts Co., Ltd. joined hands with DaimlerChrysler Automobile Co., Ltd. to start mass production of ABS 8.0, TCS 8.0, ESP 8.0, ESP plus and other wire controlled hydraulic brake systems, which are configured on medium and high-end models of various styles [6].

Research on heat recovery system technology. Chen *et al*. [7] discussed and analyzed the management and utilization theory of waste heat energy at all levels of the engine (exhaust heat, cooling water heat, accessory cooler heat) and the control strategy of energy flow in the early stage, and proposed the method of system model construction. Chen *et al*. [8] carried out a similar study, carried out relevant research on the exhaust heat energy recovery technology on a heavy-duty supercharged Diesel engine with exhaust gas re-circulation, and proposed a two-stage recovery system to simultaneously recover the multi-stage waste heat of the engine, the scheme can simultaneously recover the energy of exhaust residual heat, cooling water residual heat, exhaust gas re-circulation cooling waste heat and intake intercooling waste heat. Through multi-stage energy recovery, the output power of the engine can be increased, the engine economy can be improved and CO_2 emissions can be reduced. Xia *et al*. [9] have developed a dual cycle system to recover the residual heat energy of the engine, the two cycle systems use H_2O and ethanol as working fluids, respectively. The first stage cycle recovers the residual heat energy of the engine, and the second stage cycle is used to further recover the energy that cannot be recovered in the first stage cycle. Through the joint action of the two-stage cycle, the residual heat energy can be fully utilized. The bench test results show that the system can increase the effective thermal efficiency of the engine by about 15%. Chu *et al*. [10] extended the single point working condition multiple steady-state working conditions, proposed the structural design of evaporator and engine cylinder head integration and the design of three layers of cooling channels around the combustion chamber from the perspective of energy management, so as to maximize the available energy of the engine. The test results show that the engine efficiency is increased by 13.2%. However, the complexity and high cost of the system, as well as how to improve the thermal efficiency of the system under low load and how to match with the hybrid power system, need further exploration. Zhang *et al*. [11] carried out research on issues related to waste heat recovery technology on hybrid electric vehicles. Using water and organic substances as working fluids, the engine exhaust and cooling water waste heat are recycled in steps to improve the engine fuel utilization as much as possible. The results show that the scheme of steam Rankine cycle to recover energy from a single heat source (exhaust) can save fuel by 18%. The use of organic Rankine cycle to simultaneously recover the energy of exhaust and cooling water can improve the fuel saving efficiency of the engine to 32%. Based on the gasoline engine of Toyota Prius hybrid vehicle, Wang *et al*. [12] conducted a comparative analysis of three waste heat energy recovery schemes (recovery of exhaust energy by Rankine cycle, recovery of exhaust and cooling water energy by Rankine cycle, and combination of recovery system and engine block). The results show that the scheme of directly using the engine cooling system as the heat exchange component of the cycle can greatly simplify the complexity of the whole system, and can significantly improve the overall efficiency of the engine, the practical application prospect is better than the other two schemes. Chen *et al*. [13] used the simulation method to expand the working conditions of the engine to the full working conditions, the results showed that the fuel conversion efficiency of the engine could be improved by 5.1% on average by using the waste heat energy recovery technology, up to 8.2%.

On the basis of the current research, the author proposes a friction heat recovery system based on the hydraulic brake by wire system of heavy-duty vehicles, which uses the heat generated by friction generate electricity and stores the electrical energy in the vehicle battery. This cannot only provide power for the lighting equipment on the vehicle, but also reduce fuel consumption and environmental pollution.

Methods

Basic structure of HBW

Figure 1 is a schematic diagram of the composition of the HBW system of 1/4 heavy-duty vehicles, which is composed of three modules: electronic control unit module, hydraulic control unit module, and electronic brake pedal module. The electronic brake pedal contains a brake force sensor and a brake torque sensor, as the main component of the electronic brake pedal module, it collects the voltage signal of the electronic pedal and transmits the brake signal to the electronic control unit, the ECU converts the brake voltage signal into the corresponding PWM waveform output to control the solenoid proportional valve, and controls the output of oil through the spool displacement.

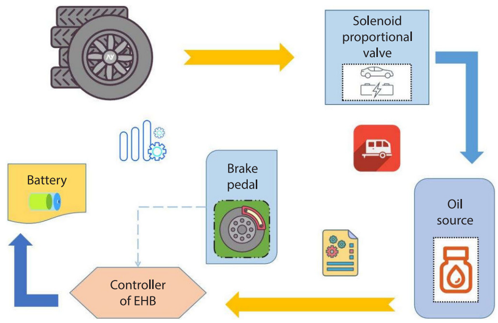

Figure 1. Hydraulic brake system by wire of heavy vehicle

The hydraulic control unit includes the fluid reservoir, hydraulic pump, motor, one-way valve, filter, overflow valve, high pressure accumulator, electromagnetic proportional valve wheel cylinder pressure sensor and accumulator pressure sensor. The hydraulic control unit receives the signal from the ECU, controls the working state of the motor pump through the relay, and completes the charging process of the accumulator. According to the proportional output characteristics of the electromagnetic proportional valve, HBW can complete the process of linear pressurization, pressure maintenance and linear decompression. With the increasing travel of the electronic pedal, the ECU converts the brake signal into a PWM output to control the left displacement of the solenoid proportional valve spool, the brake fluid enters the brake wheel cylinder from the high pressure accumulator through the solenoid proportional valve, which is a pressurization process. When the electric signal of the electronic pedal maintains a certain value, the solenoid proportional valve maintains a certain opening, so that the oil flow into the wheel cylinder in a unit time is the same as the oil flow to the tank, which is a pressure maintaining process. When the electric signal of the electronic pedal weakens, the spool of the electromagnetic proportional valve moves to the right, the brake fluid in the wheel cylinder flows to the oil tank, and the brake pressure decreases, this is a pressure reduction process.

The HBW system model

The hydraulic control unit includes the fluid reservoir, hydraulic pump, motor, one-way valve, filter, overflow valve, high pressure accumulator, electromagnetic proportional valve wheel cylinder pressure sensor and accumulator pressure sensor. The hydraulic control unit receives the signal from the ECU, controls the working state of the motor pump through the relay, and completes the charging process of the accumulator. According to the proportional output characteristics of the electromagnetic proportional valve, HBW can complete the process of linear pressurization, pressure maintenance and linear decompression. With the increasing travel of the electronic pedal, the ECU converts the brake signal into a PWM output to control the left displacement of the solenoid proportional valve spool, the brake fluid enters the brake wheel cylinder from the high pressure accumulator through the solenoid proportional valve, which is a pressurization process. When the electric signal of the electronic pedal maintains a certain value, the solenoid proportional valve maintains a certain opening, so that the oil flow into the wheel cylinder in a unit time is the same as the oil flow to the tank, which is a pressure maintaining process. When the electric signal of the electronic pedal weakens, the spool of the electromagnetic proportional valve moves to the right, the brake fluid in the wheel cylinder flows to the oil tank, and the brake pressure decreases, this is a pressure reduction process [14].

The HBW system control

Accumulator control, hydraulic control unit based on preset pressure value, control the working process of motor pump through relay. The electronic control unit determines the working state of the motor pump by controlling the on-off of the relay. Due to the existence of the upper limit of the accumulator's charging pressure, the pressure fluctuation is large and the charging speed is fast, the pressure range of the accumulator is set between the lower limit of the working pressure and the upper limit of the working pressure, when the accumulator is charged from the motor pump until its pressure is greater than the lower limit of the working pressure, the electric control unit control relay turns off the motor and stops charging. When the accumulator is filled with liquid until its pressure is less than the lower limit of working pressure, the electronic control unit controls the relay to start the motor to fill liquid until the pressure reaches the upper limit of working pressure.

The brake pressure control and wheel cylinder pressure regulation process adopt PID controller. The PID controller regulates the input electrical signal as the controller input according to the difference between the actual brake pressure and the target expected pressure, and outputs it to the electromagnetic proportional valve of the hydraulic brake system by wire through the controller, after the PID controller controls the difference between the brake target pressure and the actual brake pressure, the HBW system can ideally output the pressure according to the desired brake force. The wheel cylinder pressure sensor converts the voltage signal corresponding to the pressure into the electronic control unit through the AD module, and the electronic control unit performs mean filtering on the data to obtain the difference between the target pressure and the actual pressure, the PID controller is used to control the error until the actual pressure is more and more close to the target pressure, and the PWM signal output is calculated [15].

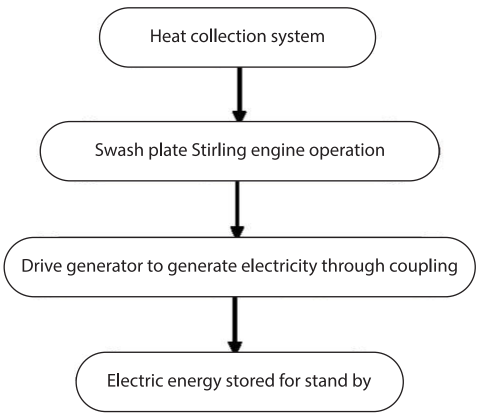

Figure 2. Recovery flow chart of thermal energy system

Flow chart of heat recovery system

The recovery process of the heat energy system is shown in fig. 2, the heat collection system is divided according to the working temperature in the heat pipe, the heat pipe can be divided into low temperature heat pipe (–273-0 °C), normal temperature heat pipe (0-250 °C), medium temperature heat pipe (250-450 °C), high temperature heat pipe (450-1000 °C), *etc*. According to the temperature field analysis and distribution law research of tail gas, the heat pipe adopts star shaped circular distribution, the heat pipe distributed in the middle is high temperature heat pipe, and the heat pipe distributed at the outer edge is medium temperature heat pipe. In order to avoid a large amount of tail gas gathering in the heat collection hood after cooling, symmetrical through-hole shall be opened on the wall of the heat collection hood, so that the cooled waste gas can be discharged from the hole in time to prevent the increase of exhaust pipe back pressure. The arrangement and size of the through-hole can be measured and calculated through the exhaust gas-flow and pressure experiment. The other end of the heat pipe group is connected with the circular radiating fins, the radiating fins are placed in the heat collection box, the wall of the heat collection box is provided with insulating materials through the heat conduction of the heat pipe. The heating tube of the swashplate Stirling engine is surrounded by annular radiating fins. This ensures that there is enough heat to enable the swashplate Stirling engine to work in a cycle [16].

Swash plate stirling engine, stirling cycle is based on Carnot cycle principle, including four cycle processes of isothermal expansion, equal volume heat release, isothermal compression and equal volume heat absorption. The swashplate transmission mechanism is superior to diamond and crank transmission mechanisms in compactness, noise and transmission efficiency. Assuming the ideal cycle, the heat absorption and heat release of the regenerator are equal in the process of heat release and heat absorption of equal volume, the work efficiency of Stirling heat engine to the outside in the whole cycle is:

$$\eta = 1 - \frac{T_1}{T_2} \tag{1}$$

where T_1 is the temperature of the hot chamber and T_2 is the temperature of the cold chamber.

Transmission and power generation system: the output shaft of the swashplate Stirling engine is connected with the three-phase alternator through the coupling, the rotation of the output shaft drives the generator to generate electricity, and the generator is connected with the vehicle battery to store the electric energy as the lighting power on the vehicle.

Results and discussion

The experimental results are shown in fig. 3. It can be seen from the figure that braking energy consumption decreases after using the recovery system. Moreover, the fuel consumption is 10% less than before, which fully demonstrates the effectiveness of the recovery system for energy conservation [17-20].

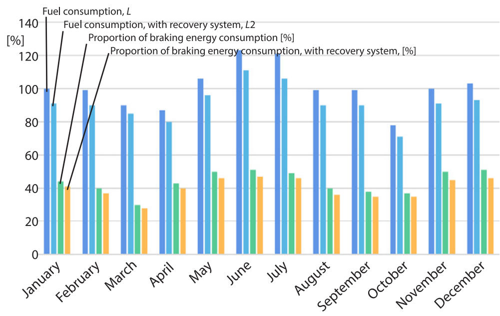

Figure 3. Effect of recycling system

Conclusion

To sum up, converting the friction waste heat of the hydraulic brake system by wire of heavy-duty vehicles into electric energy and using it for vehicle lighting cannot only reduce fuel consumption, but also save energy to a certain extent. Through the aforementioned modelling and simulation analysis, it is preliminarily believed that the waste heat recovery system is feasible. The system can be used as a reference scheme to recover heat energy.

Acknowledgment

The study was supported by National Natural Science Foundation of China The spectral element discrete critical point method of the solution space based on the equivalent volumetric strain static load and its using on structural dynamic response optimization (Grant No. 51275489) and Natural Science Foundation of Shanxi Province of China The basic study on the streamlined equivalent static load of multi-substructure and the dynamic response optimization of complex structure with rigid body mode separation analytical gradient based on Energy evaluation PDOFs (Grant No. 201701D121082).

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Paper submitted: August 5, 2022
Paper revised: October 2, 2022
Paper accepted: October 20, 2022