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Experimental Study on the Influence Factors of the Recovery Rate of the Braking Energy of Electric Control & Hydro-Drive Hybrid Vehicle

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Experimental Study on the Influence Factors of the Recovery Rate of the Braking Energy of Electric Control & Hydro-Drive Hybrid Vehicle

Lei Xu, Xiaohui He*, and Qiang Wang, Yaowei Yu

College of Field Engineering, PLA Army Engineering Nanjing, China

*Corresponding author e-mail: xustak0708@outlook.com

Abstract. It is important to improve the fuel economy and environmental protection of the hybrid vehicles by using the energy regenerative braking system to realize the braking energy recovery. In order to confirm the main factors that affect the recovery rate of the braking energy of the hybrid electric vehicle, according to the theoretical analysis results of the braking energy recovery, the related experiments were designed, and the verified experiments of the braking energy recovery rate under different braking intensity, under different initial pressure of accumulators and under different braking initial speed required finishing. The experimental results showed that when the braking intensity was 0.4, the initial pressure of the accumulators was 19MPa and the braking initial speed was 300rpm, the maximum recovery rate of braking energy can be reached by the experiment, which can reach 83.33%.

1. Introduction

The energy-regenerative braking systems in hybrid vehicles can be used to recycle braking energy, to save energy, to reduce polluted gas emissions, and to protect the environment [1, 2]. As an important type of hybrid vehicles, electric control & hydro-drive hybrid vehicle was based on the internal combustion engine as the original power source, controlled by the electronic unit, with hydraulic drive. It is the ideal model of large construction machinery and special vehicles in the future [3, 4], with many advantages such as large driving force, flexible control, fuel economy. As an important index to measure the performance of hybrid vehicles, the research on the influence factors of braking energy recovery is one of the hotspots of vehicle performance research. It is of great significance to improve the recovery rate of braking energy by optimizing the influence factors, and to increase the fuel economy and environmental protection of the hybrid vehicles [5, 6].

At present, the research of hybrid vehicle mainly has been concentrating on the electric hybrid technology, coupled with the enthusiasm of the major enterprises for the electric vehicle in recent years, the research on the electric control & hydro-drive hybrid technology was almost shelved. Compared with the electric hybrid technology and electric technology, the electric control & hydro-drive hybrid technology is more effortlessly used in the operation of frequent start and stop during the driving process to reclaim more braking energy. The researches and analysis of the influence factors of braking energy recovery of hybrid vehicles mainly focus on the selection of auxiliary power sources, including storage battery, mechanical flywheel, hydraulic accumulators and super capacitor, in which hydraulic accumulators converse energy in physical way, so that the rate of braking energy conversion and the rate of recovery was higher relatively. For electric control & hydro-drive hybrid vehicle which uses the hydraulic accumulators as the auxiliary power source, the different system structure (the power elements arrangement pattern) affects the rate of braking energy recovery. Among the three kinds of system structure (the series, the parallel and the mixed), the rate of braking energy recovery in the series pattern is maximum. Since there are several factors influencing the recovery rate of braking energy, and there is limited analysis on the external influence factors of the braking energy recovery of the vehicle with series structure [7, 8]. However, this paper mainly analyzed the influence of the external conditions of the system on the recovery of braking energy and optimizes the combination of different influencing factors to obtain the maximum rate of braking recovery.

Aiming at the problems that the influence factors of recovery rate of braking energy were difficult to be clear. Firstly, the necessary theoretical calculation and analysis of the system were carried out, then the relevant experiments were accomplished by using the experimental bench, the best combination of the influencing factors of the braking energy recovery rate was obtained at last.

2. theoretical analysis of of the recovery rate of the braking energy

Schematic diagram of a series of electric control & hydro-drive hybrid vehicle system was shown in Fig. 1. When the vehicle was running, the engine was the original power source of the whole vehicle, the hydraulic pump/motor worked in the hydraulic motor working condition. When the vehicle was braking, the hydraulic pump/motor worked in the pump working condition, and the wheel worked as a power source, driving the hydraulic pump/motor to turn mechanical energy into hydraulic energy, which was stored in the high-pressure accumulators, and was released when starting or accelerating again, to achieve the purpose of energy saving.

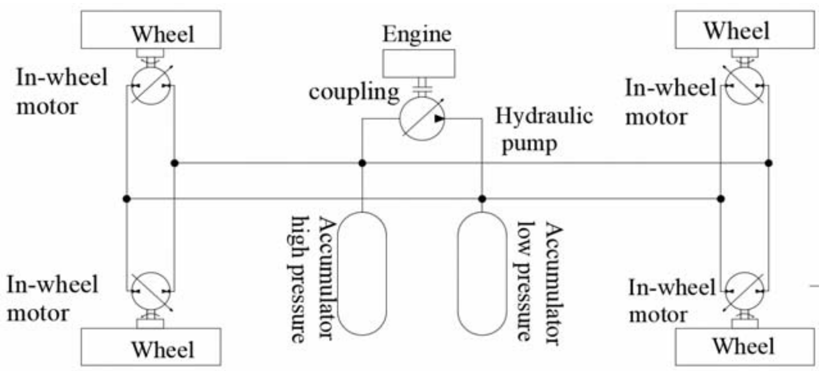

Figure 1. Schematic diagram of a series of electrically controlled liquid drive hybrid vehicle system

As the key component of energy regenerative braking system, the hydraulic accumulators have a great influence on the recovery rate of braking energy. As the main energy conversion element, the gas is usually changed with the temperature when the energy changes (between isothermal process and adiabatic), so the dissipation of heat dissipation should be taken into account in calculating the recovery rate of braking energy. The dissipation of heat is mainly related to the gas variability index *n*, and the *n* is related to the change in the volume of gas in the accumulators, current traffic was shown in Eqs. (1).

$$n = \frac{0.4}{q_{\max}} q_a + 1 \tag{1}$$

A complete list of parameters and variables is given below:

$q_{\max}$: The maximum flow rate for the pipeline connected to the accumulators, m3/s

q_a : The current traffic, m3/s

Considering the heat dissipation, the energy change corresponding to the pressure change of the hydraulic accumulators was shown in Eqs. (2).

$$E_{\mathrm{h}} = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} P_0 (\frac{V_0}{V})^{\frac{0.4}{q_{\max}} q_a + 1} \mathrm{d}V \tag{2}$$

A complete list of parameters and variables is given below:

E_{h} : The value of the energy change under adiabatic, J

V_1 V_2 : The nitrogen volume before and after the change, m3

P_0 : The pre-charged nitrogen pressure, Pa

V_0 : The volume of gas corresponding to the pre-charged nitrogen pressure, m3.

Assume that the temperature in the accumulators does not change before and after the change (n=1.4), the pressure change of the hydraulic accumulators corresponding to the energy change was shown in Eqs. (3) and (4).

$$E = \int_{V_1}^{V_2} P dV = \frac{P_0 V_0}{0.4} \left[\left(\frac{P_1}{P_0} \right)^{\frac{0.4}{1.4}} - \left(\frac{P_2}{P_0} \right)^{\frac{0.4}{1.4}} \right] \tag{3}$$

$$E_r = E - E_{\mathrm{h}} \tag{4}$$

A complete list of parameters and variables is given below:

E : The value of the energy at the isothermal temperature, J

P_1 P_2 : The pressure value of accumulators before and after the change, and the, Pa

E_r : The heat dissipation, J

Other than the heat dissipation, the accumulators in the recovery of braking energy also exists along the process of pressure dissipation and local pressure dissipation (pipe fittings and elbow), in order to simplify the calculation, the local pressure dissipation is replaced by the pressure dissipation (substituted by equivalent pipe length), and the pressure dissipation between the two hydraulic elements can be calculated, which was shown in Eqs. (5).

$$\Delta P_{\mathrm{L}} = \frac{\rho f_{\mathrm{L}} L_{\mathrm{e}} Q_{\mathrm{L}}}{2DA^2} \tag{5}$$

The flow dissipation can be shown as Eps. (6).

$$W_{\mathrm{L}} = \int_0^{\mathrm{t}} \Delta P_{\mathrm{L}} Q_{\mathrm{L}} dt \tag{6}$$

When the vehicle started to recycle the braking energy, the hydraulic accumulators started to be charged under the pre-filling nitrogen pressure, the hydraulic accumulators were filled as the system pressure achieved the maximum working pressure, at this time, the surplus braking energy can flow back to the low-pressure system pipeline only through the overflow valve, which can no longer be stored by the hydraulic accumulators. The recovery rate of the braking energy was defined as the ratio of the energy recovered by the accumulators to the vehicle kinetic energy before and after the braking. The recovery rate of the braking energy can be expressed in Eps. (7).

$$\eta_{\mathrm{acc}} = \frac{\int_{V_1}^{V_2} P\mathrm{d}V - E_r - W_L}{\frac{1}{2}m(v_1^2 - v_0^2)} = \frac{\int_{V_1}^{V_2} P_0(\frac{V_0}{V})^{\frac{0.4}{q_{\max}}q_a + 1}\mathrm{d}V - W_L}{\frac{1}{2}m(v_1^2 - v_0^2)} \tag{7}$$

We can conclude that the main factors influencing the recovery rate of the braking energy were the initial pressure of the accumulators, the value and the range of speed change of the inertia flywheel (which affects the system pressure dissipation) after profiling Eps. (7). the following designed experiments were to further verify the results of theoretical analysis.

3. Experimental Research

The energy regenerative braking system of the electric control & hydro-drive hybrid vehicle mainly consisted of accumulators, hydraulic pump/motor, inertia flywheel, fuel tank and sensors and other components, the system working principle was shown in Fig. 2. Accumulators, hydraulic pump/motor and inertia flywheel converse energy each other between hydraulic and mechanical under the control of the controller, to achieve the braking energy recovery and reuse.

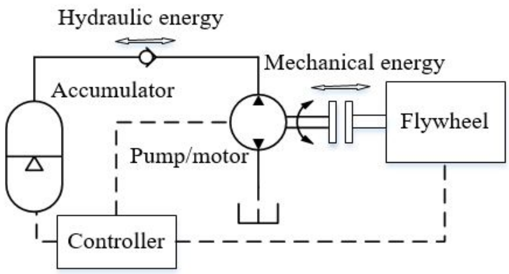

Figure 2. Working principle of energy regenerative braking system

3.1. Experimental Bench Principle

After analyzing the principle of energy regenerative braking system, the experimental bench was established to carry out further experimental research on the braking energy recovery of the regenerative braking system, and the system principle of the experimental bench was shown in Fig. 3. The motor was used to replace the internal combustion engine of the original vehicle, driving the hydraulic pump as the main power source. The accumulators can be used as the energy storage element in the braking working condition, as auxiliary power source in the driving. The maximum operating pressure of the system was limited by the electromagnetic overflow valve, at the same time, the operating pressure of the system was controlled by the proportional overflow valve in actual time. The inertia flywheel was equivalent to the moment of inertia of the original vehicle. In the system, many kinds of pressure sensors, torque and speed sensors, temperature sensors and flow sensors were used to monitor the operation of the system.

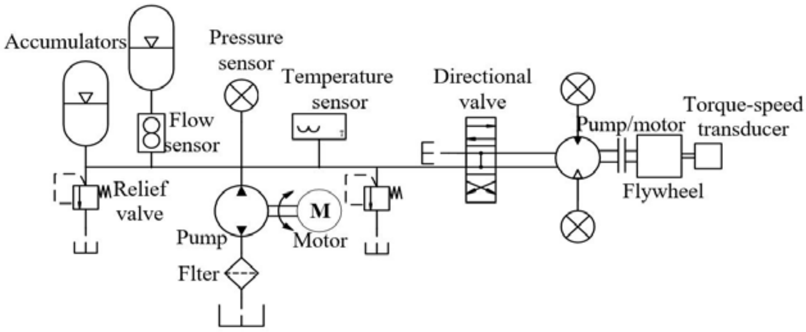

Figure 3. Principle of Lab bench system

The control system of the experimental bench was composed based on the TMS320F2812 digital signal processor and correlative data acquisition module, which can control and collect the crux components in the experimental bench.

Design related experiments according to the results of the theoretical analysis, mainly divided into three types of experiments: different braking intensity, different initial pressure of accumulators and different braking initial speed.

3.2. Braking Energy Recovery Experiments under Different Braking Intensity

Recharge the accumulators to 19MPa (which can drive rotational velocity of flywheel to 350rpm maximum, to meet experimental requirements), drive inertia flywheel to 300rpm (the speed of the equivalent prototype vehicle is 136km/h), start braking, and change braking intensity z (0.3-0.5. $z=\frac{a}{g}$, a is braking deceleration, g is gravitational acceleration). The rotational velocity of the inertia flywheel and the pressure of the accumulators was shown in the results of the experiment and post-processing was illustrated in Fig. 4 and Fig. 5.

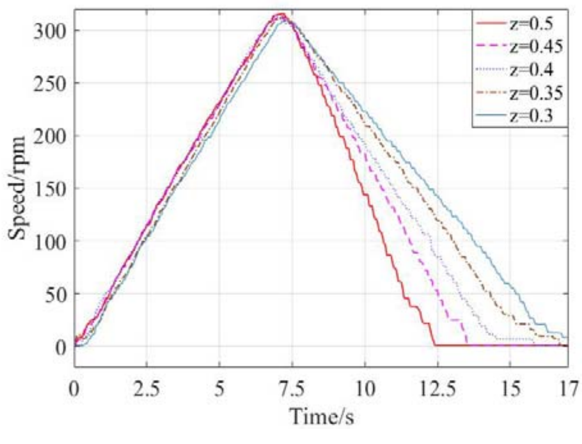

Figure 4. Inertia flywheel speed change with time

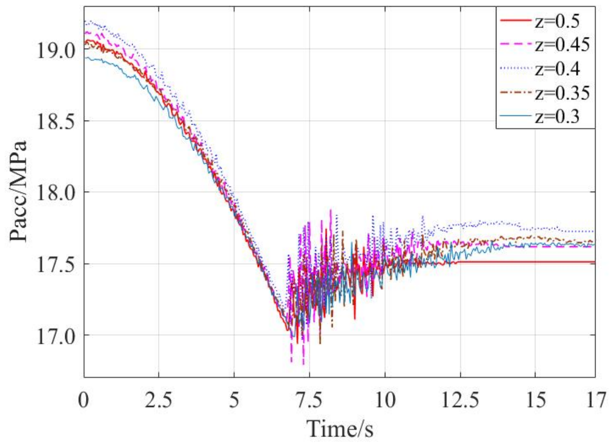

Figure 5. Accumulators pressure change with time

From Fig. 4 and Fig. 5, we can know that pressure of accumulators were fluctuating when it started recovery braking energy, because the pressure of the hydraulic system was very large. The flow of hydraulic oil suddenly reversing, will have a strong impact on the entire hydraulic system, and the pressure of the accumulators to appear fluctuations in the results. After further data processing, the experimental results of braking energy recovery under different braking intensity were shown in the table 1.

Table 1. The experimental results of braking energy recovery under different braking intensity

Breaking Strength	Initial Pressure /MPa	Initial Speed /rpm	Breaking Time/s	Kinetic Energy Change/J	Recovery Energy/J	Recovery Rate/%
0.3	19	300	10.12	56750	45042	79.37
0.35	19	300	9.33	56750	45882	80.85
0.4	19	300	7.45	56750	46722	83.33
0.45	19	300	6.51	56750	42518	74.92
0.5	19	300	5.50	56750	38305	67.49

The data in the table 1 showed that at the same initial speed of braking, with the increase of braking intensity, the maximum rate of braking energy that can achieve 83.33%, when z=0.4.

3.3. Braking Energy Recovery Experiments under Different Initial Pressure of Accumulators

Keep braking intensity z=0.4. Drive the inertia flywheel to 300rpm to brake under different initial pressure (19MPa-22MPa) individually. The rotational velocity of the inertia flywheel and the pressure of the accumulators through experimental and post-processing results as shown in Fig. 6 and Fig. 7.

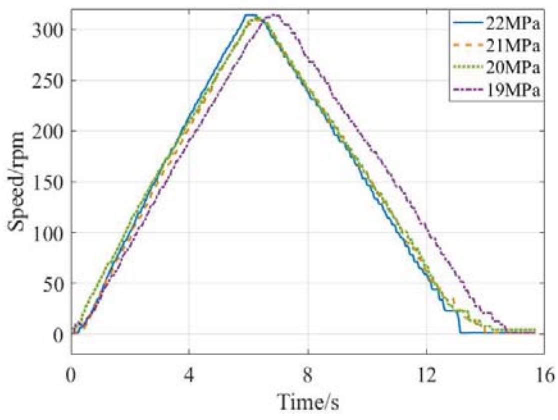

Figure 6. Inertia flywheel speed change with time

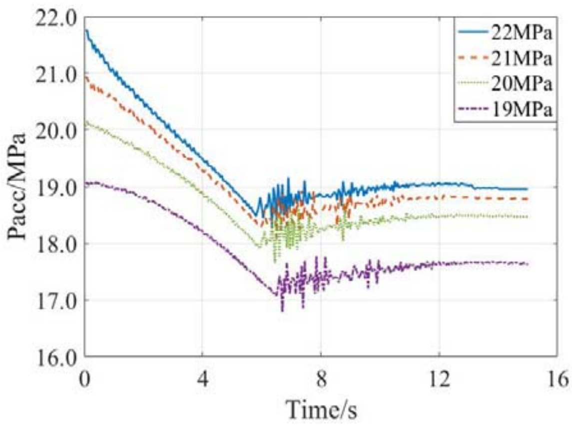

Figure 7. Accumulators pressure change with time

From Fig. 4 and Fig. 5, we can know that when the initial pressure of the accumulators was 21MPa and 22MPa, the pressure varies of 19MPa and 20MPa were much smaller, because of the working characteristics of the experiment bench itself and the higher-pressure dissipation when the system pressure was high. After further data processing, the experimental results of braking energy recovery under different initial pressure of accumulators were shown in the table 2.

Table 2. The experimental results of braking energy recovery under different Initial Pressure of Accumulators

Breaking Strength	Initial Pressure /MPa	Initial Speed /rpm	Breaking Time/s	Kinetic Energy Change/J	Recovery Energy/J	Recovery Rate/%
0.4	19	300	7.43	56750	46722	83.33
0.4	20	300	7.27	56750	46603	82.12
0.4	21	300	7.22	56750	43260	76.23
0.4	22	300	7.23	56750	39231	69.13

It showed that with the increase of the initial pressure of the accumulators, the recovery rate of braking energy showed a slight downward trend, because of the increase of accumulators pressure and the working characteristics of the accumulators, the difficulty of recovery of braking energy was increased, which lead to the reduction of recovery rate of the braking energy.

3.4. Braking Energy Recovery Experiments under Different Initial Breaking Speeds

Keep braking intensity z=0.4, charge accumulators to 19MPa. Drive the inertia flywheel to braking at different initial velocity, the rotational velocity of the inertia flywheel and the pressure of the accumulators through experimental and post-processing results were shown in Fig. 8 and Fig. 9.

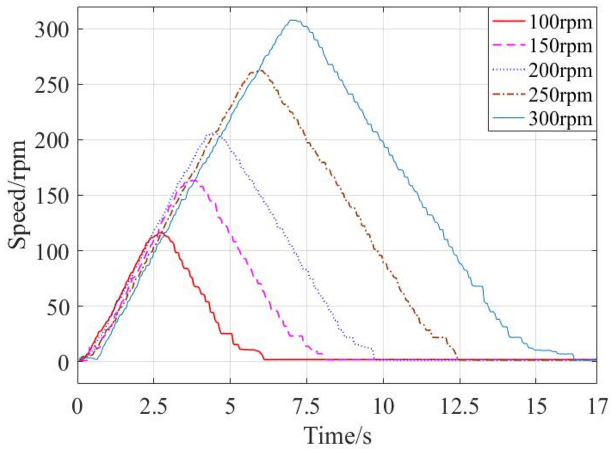

Figure 8. Inertia flywheel speed change with time

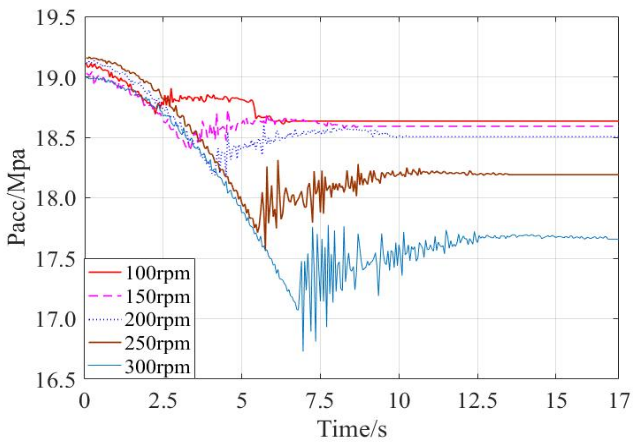

Figure 9. Accumulators pressure change with time

From Fig. 8 and Fig. 9, we can know that when the inertia flywheel was braking at the initial speed of 100rpm and 150rpm, the effect of regenerative braking is not better than 250rpm and 300rpm. The reason was that braking initial velocity was too small after preliminary analysis, coupled with the accumulators itself pressure dissipation, resulting in lower recovery. After further data processing, the experimental results of braking energy recovery under different initial pressure of accumulators were shown in table 3.

Table 3. The experimental results of braking energy recovery under different Initial Pressure of Accumulators

Breaking Strength	Initial Pressure /MPa	Initial Speed /rpm	Breaking Time/s	Kinetic Energy Change/J	Recovery Energy/J	Recovery Rate/%
0.4	19	100	2.21	6035	4479	74.22
0.4	19	150	3.89	13579	10359	76.29
0.4	19	200	4.81	25222	20501	81.28
0.4	19	250	6.18	37719	31310	83.01
0.4	19	300	7.45	56750	46722	83.33

From the data in the table 3 we can conclude that with the increase of the initial speed of the inertia flywheel, braking energy recovery will also have a slight rise, when braking at the higher braking initial speed, the accumulators can work much longer, so as to reclaim more braking energy.

4. Conclusion

(1) Based on the theory of braking energy recovery, according to the principle of system work and energy management, the paper analyzed the braking energy recovery of electric control & hydro-drive hybrid vehicle theoretically, and from the analysis structure, it can be seen that the main factors influencing the recovery of braking energy were the initial pressure of accumulators, the value and the range of speed change of the inertia flywheel (which affects the system pressure dissipation).

(2) Based on theoretical analysis, the experimental bench for energy regenerative braking system of electric control & hydro-drive hybrid vehicle was established. The results showed that the results of the theoretical analysis were reasonable, and the recovery rate can achieve 83.33%.

(3) Through theoretical analysis and experimental verification, the feasibility of using energy regenerative braking system to realize braking energy recovery was verified, which provided technical support for popularization and application of HEV.

Acknowledgments

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