Research on the Energy Recovery System of an Electric Controlled Hydro-hybrid Vehicle

Tao Zhang, Qiang Wang, Xiaohui He*, Sisheng Li

College of Field Engineering, PLA Army Engineering University, China

*Corresponding author e-mail:15651722550@163.com

Abstract. The parameter configuration of the energy recovery system affects significantly the braking performance and energy-saving effect of hydro-hybrid vehicles. The working principle of the energy recovery system of an electric controlled hydro-hybrid vehicle was analysed. Based on quarter of the prototype vehicle, the parameters of auxiliary power element (accumulator) and secondary element (hydraulic pump/motor) were analysed theoretically. The test verification was carried out based on the test bench. It was shown that on the premise of satisfying the braking performance, reducing the minimum working pressure of the accumulator was beneficial to the recovery of braking energy. The displacement of the hydraulic pump/motor has a great influence on braking performance and a little effect on the recovery rate of braking energy. Furthermore, the lower the working pressure of the accumulator, the larger the energy density.

1. Introduction

The powertrain of the electric controlled hydro-hybrid vehicle mainly consists of a diesel engine, a constant pressure variable pump, a high-voltage accumulator, a low-voltage accumulator (instead of a hydraulic oil tank), variable displacement hydraulic pump/motor, directional control valves and the control system. The power transmission path from the diesel engine to hydraulic motors/pumps is in series (Figure 1).

The diesel engine directly drives a constant pressure variable pump which adjusts the displacement to maintain the constant pressure of the hydraulic system [1-2], so the working condition of the engine is basically independent of the external load to work in the area with high fuel economy. Each wheel is driven independently by a hydraulic pump/motor which can work in four quadrants. In the drive phase, the hydraulic pump/motor is in the "Motor" state which converts pressure energy to mechanical energy and the vehicle can achieve infinite speed regulation by adjusting the displacement of the hydraulic pump/motor. In the braking phase, the hydraulic pump/motor is in the "Pump" state and converts the kinetic energy of the vehicle into the hydraulic energy stored in the accumulator which can be reused in the drive phase.
The main components of the energy recovery system include accumulators, hydraulic pumps/motors, and their parameter configuration has a great impact on system performance. In recent years, there are many scholars who studied the influence of variable parameters on energy recovery of parallel hybrid power systems based on the established simulation model of recycling systems [3], and the basic laws of system parameter configuration is obtained. Furthermore, the parameters of accumulator volume, hydraulic pump/motor displacement of series hydraulic hybrid vehicles are optimized by simulated annealing algorithm, genetic algorithm and hybrid biogeography HBBO algorithm [4], in which the fuel economy can be improved by more than 7% after parameter optimization.

In this study, the necessary theoretical calculation and analysis of this series system were carried out, the relevant experiments were accomplished by using a test bench, and the laws of parameters configuration were obtained at last.

2. Main component parameters affecting energy recovery performance

2.1. hydraulic pump/motor

On this vehicle, the output power of the hydraulic pump/motor is shown in equation 1.

\[ P_{\text{p/m}} = T_{\text{p/m}} \omega_{\text{p/m}} \]  

where, \( T_{\text{p/m}} \): Output torque of the hydraulic pump/Motor, Nm
\( \omega_{\text{p/m}} \): Output rotational speed of the hydraulic pump/Motor, rad/s

When the vehicle is in drive state, the hydraulic Pump/motor works in the "Motor" condition. The requirements of minimum output power and maximum power of the motor are shown in equation 2 and equation 3[5]

\[ (P_{\text{p/m}})_{\text{min}} = \frac{1}{3600 h_{\text{p/m}}} (mg f + \frac{C_D A v_{\text{avg}}^2}{21.15}) v_{\text{avg}} \]  

\[ (P_{\text{p/m}})_{\text{max}} = \max(P_{\text{p/m}1}, P_{\text{p/m}2}) \]

where, \( v_{\text{avg}} \): Cruising speed, m/s
\( v_{\text{up}} \): Uphill speed, m/s
\( m \): Mass of the vehicle, kg
\( C_D \): Wind-resistance coefficient
\( A \): Face area, m²
\( f \): Rolling resistance coefficient of pavement
\( \alpha \): Angle of gradient of the road, °
\[ \left( P/m_{1}\right) = \frac{1}{3600 \eta_{pm}} \left( mg f + \frac{C_{D} A v_{m}^2}{21.15} \right) v_{max} \]  

(4)

\[ \left( P/m_{2}\right) = \frac{1}{3600 \eta_{pm}} \left( mg f + \frac{C_{D} A v_{m}^2 + mgsin\alpha}{21.15} \right) v_{slop} \]  

(5)

When the vehicle is in braking state, the hydraulic pump/motor works in the "Pump" condition.

\[ T = \frac{\Delta P V_{pm}}{2\pi} \]  

(6)

where, \( T \) : Braking torque, Nm

\( \Delta P \) : Pressure difference between Import and export of hydraulic pump/motor, MPa

\( V_{pm} \) : Displacement of pump/motor, m³/r

2.2. Accumulator

For the hydraulic accumulator, the working medium (nitrogen) can be regarded as an independent thermodynamic system, through it can not be separated from the external environment.

The laws of gas changing processes are shown equation 7

\[ P_{0} V_{0}^{n} = P_{1} V_{1}^{n} = C \]  

(7)

where, \( P_{0}, P_{1} \) : Accumulator pre-charge pressure and minimum working pressure respectively, MPa

\( V_{0}, V_{1} \) : Corresponding volume of gas for \( P_{0}, P_{1} \) respectively, m³

\( n \) : Gas polytropic exponent 1.2

\( C \) : Constant

The accumulator volume-pressure curve used in this study is shown in figure 2.

![Volume-pressure curve of accumulator](image)

Figure 2. Volume-pressure curve of accumulator

According to the working principle of the hybrid vehicle, the minimum working pressure of the accumulator should be lower than the system pressure of the constant pressure network, and the maximum working pressure should be lower than the maximum working pressure allowed by the hydraulic pump/motor, as is shown in equation 8 and equation 9.

\[ P_{acc, min} < P_{const} \]  

(8)

\[ P_{acc, max} \leq P_{max} \]  

(9)

where, \( P_{const} \) : System pressure of the constant pressure network, MPa

\( P_{max} \) : Maximum pressure allowed by hydraulic pumps/motors, MPa

The volume of the accumulator volume should be determined by the kinetic energy of the vehicle at cruising speed.

\[ E_{1} \geq E_{2} \]  

(10)
where, $E_1$: Energy recovered by accumulator

$$E_1 = \int_{v_i}^{v_f} PdV = \frac{P}{n-1} \left[ \frac{V}{V_i}^{\frac{1}{n-1}} \right]$$

$E_2$: Kinetic energy of vehicle at cruising speed

$$E_2 = \frac{1}{2} m v^2$$

At the same time, the energy recovery rate of the system [6] is shown in equation 13.

$$\eta = \frac{E_1}{E_2} = \frac{PV_i}{n-1} \left[ \frac{P}{P_i} \right]^{\frac{1}{n-1}} \times \frac{2}{mv^2}$$

It’s easily known from $E_1$ and figure 2 that the energy recovered by the accumulator is the curve integral. The higher the minimum working pressure of the accumulator, the larger the promotion of the accumulator pressure to recovery the same energy.

3. Test of Energy Recovery Performance

As is shown in figure 3, the test bench consists of an electric motor (instead of an internal combustion engine), a constant pressure variable pump, a high-voltage accumulator, an electrical controlled proportional variable hydraulic pump/motor, a magnetic powder brake (simulate load), flywheel (the inertia moment of the flywheel simulate the one of quarter of vehicle) and the control system. The different minimum working pressure of accumulators are set by adjusting the loop pressure and the two-position two-way valve outlet of the accumulator. The parameter setting window (45~5) on the software CCS is correspond to the displacement of hydraulic pump/motor (0 mL/r ~180 mL/r).

The influence of the parameters (minimum working pressure, hydraulic pump/motor displacement) on the energy recovery is studied by the control variable method. The working conditions are shown in the table 1.

| Conditions | Minimum working pressure of accumulator/bar | Hydraulic pump/motor displacement/(mL/r) |
|------------|--------------------------------------------|------------------------------------------|
| 1          | 180                                        | 180                                      |

Procedure of test: Charge the accumulator first, then drive the flywheel to 840 rpm. Brake the flywheel to 0 rpm. The test results are shown in figure 4 and figure 5.

Figure 4 is the curve of parameters corresponding to the different minimum working pressures of the accumulator (170bar, 175bar, 180bar), and it can be seen that the change amplitude of accumulator pressure are different under the different minimum working pressures of accumulator. The higher the
minimum working pressure, the larger the promotion of the accumulator pressure to recovery the same energy, which is consistent with the theoretical results in figure 2.

![Pressure curves of accumulator](image1.png) ![Speed curves of the flywheel](image2.png)

Figure 4. Variation of parameters corresponding to the minimum working pressures of accumulator

Figure 5 is the change curve of parameters corresponding to different displacements of the hydraulic pump/motor, and it can be seen that the braking time corresponding to different displacement varies greatly. The pressure variation amplitude of the accumulator under the full opening (180mL/r) is quite different from one of the accumulator under the non-full opening (90mL/r, 120mL/r, 150mL/r), which is due to the displacement-efficiency curves of the hydraulic pump/motor.

![Pressure curves of accumulator](image3.png) ![Speed curves of the flywheel](image4.png)

Figure 5. Variation of parameters corresponding to the displacement of hydraulic pump/motor

When the displacement of the hydraulic pump/motor is 180mL/r and the minimum working pressures of the accumulator is 170bar, simulate the cycle condition and observe the energy utilization. The test result is shown in figure 6, $n$ is the hydraulic pump/motor rotational speed, $P$ is the loop pressure. It could be seen that the accumulator recovers energy in the braking phase and the energy is reused in the drive phase, so the fuel economy can be improved immensely.

![Pressure curves of accumulator](image5.png) ![Speed curves of the flywheel](image6.png)
4. Conclusions

(1) Increasing the minimum working pressure of accumulator and displacement of hydraulic pump/motor can lead to the increase of the braking torque and the shortening of the flywheel braking time. And, the displacement parameters of the hydraulic pump/motor have a great influence on the braking performance.

(2) Increasing the hydraulic pump/motor displacement and reducing the minimum working pressure of the accumulator are beneficial to the recovery of the braking energy. Moreover, the larger the hydraulic pump/motor displacement, the higher the recovery efficiency.

(3) The energy densities of the accumulator are different from each other corresponding to their different working pressure stage, and the lower the pressure, the larger the energy density. Next, considering the ground adhesion coefficient, the braking system of the whole vehicle and the parameter matching research will be carried out.

References

[1] Zhang Dan-dan, Zhang Xue-wei, Zhang Wei. Study on energy recovery system of parallel hydraulic hybrid vehicle based on AMESim [J]. Hydraulics and Pneumatics, 2014 (11): 100-104.

[2] Li Zi-li, Xiang Yu, Liu Chun-guang, Li Jia-q. Power flow control strategy for hybrid power system of electric drive armoured vehicle [J]. Journal of Military Engineering, 2017, 38 (12): 2289-2300.

[3] Wang Xin, Jiang Ji-hai, Yu An-cai. Optimal matching of hydraulic drive hybrid vehicle drive system [J]. Journal of Harbin Institute of Technology, 2011, 43 (07): 66-70.

[4] Zhao Bo. Parameter optimization and system simulation of hydraulic hybrid vehicle [D]. Jilin University, 2015.

[5] Liu Tao, Liu Qing-he, Jiang Ji-hai. Influencing factors of regenerative braking of parallel hydraulic hybrid vehicles [J]. Journal of Jilin University (Engineering edition), 2010, 40 (06): 1473-1477.

[6] Shabbir W, Evangelou S A. Real-time control strategy to maximize hybrid electric vehicle powertrain efficiency[J]. Applied Energy, 2014, 135(C):512-522.