A Simulation Study of the Design and Development of Vehicles Regenerative Braking System

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***Abstract* — To remove the defects of complex structures with numerous pipes, unknown dynamic parameters of hydraulic pumps, motors and flywheels of the present application of hydraulic hybrid vehicle test platform, a dynamic model of the braking energy recovery system is setup based on a novel vehicle regenerative braking system under the Matlab/Simulink simulation environment. The dynamic characteristics of this system are revealed by simulating the recovery and release conditions of the braking energy. A vehicle regenerative braking simulation test bench is built after analysis and improvements of the system. Different test conditions and models are simulated through bench tests, to validate the correctness of the dynamic design method and the practicality of the vehicle regenerative braking simulation system. This lays the foundation for subsequent experiments of hardware in loop under various conditions.**

Keywords - Hydraulic energy saving; Regenerative braking; Hardware-in-the-loop; Test bench.

I. INTRODUCTION

The technology of energy-saving and low-emission vehicles has drawn increasing attention because of environmental pollution and energy shortage. While, the braking energy recycling has become a top priority in the research of energy-saving due to a big braking energy loss caused by the low speed and frequent braking of the engineering vehicles.[1]. Hydraulic accumulator has the advantage of high power density and the ability to accept the high rates and high frequencies of charging and discharging[2].Hydraulic hybrid vehicles have a high braking intensity and energy recovery rate and make it possible to recycle and release of the vehicle braking and inertial energy with the hydraulic pumps/motors as energy conversion components and hydraulic accumulator as energy storage element, improving the fuel efficiency of engineering vehicles and heavy vehicles[3]. Therefore, it is very necessary to research the hydraulic hybrid vehicle braking energy recovery technology which is the key to whether it can be widely used in production. The present domestic Hydraulic hybrid vehicle test platform has many problems such as complex structure, numerous pipes, difficulty in the arrangement and maintenance of test beds, indefinite dynamic parameter of hydraulic pumps/motors and flywheels and the failure to combine with the electric hydraulic braking system. Thus, the design of a brand new simulation system of vehicles regenerative braking has a great significance for the research of domestic hydraulic hybrid vehicle braking energy recovery system.

This paper is about the design of a brand new hydraulic hybrid regenerative braking simulation system with simple structure and convenient arrangement based on the simulation variable of fixed displacement pump and electromagnetic valve. Based on the finished simulation test system, a dynamic simulation model is established by the use of Matlab/Simulink software so as to analyze the dynamic characteristics and then putting up the simulation test bench to make experimental verification for different test conditions and the simulation models, verifying the design methods and the practicability of the regenerative braking simulation system .

II. SYSTEM CONFIGURATION

The simulation test system of vehicle regenerative braking simulates the fluid charging and discharging process of the regenerative brake accumulator in the process of energy recovery, power drive and power allocation through adjusting pressure and flow rate.

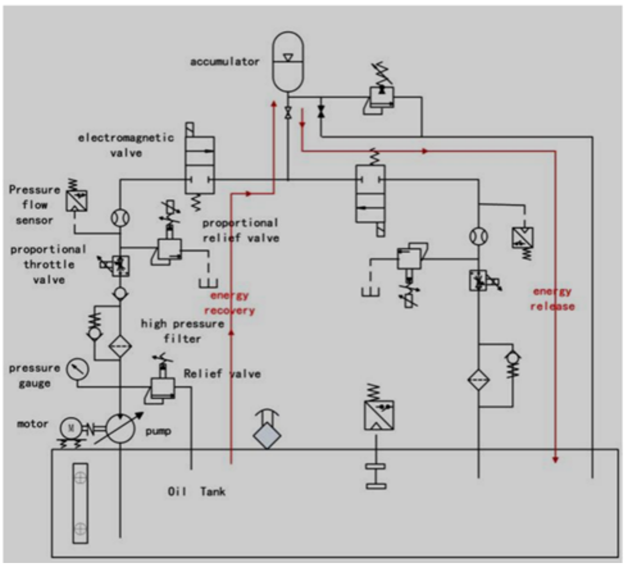

Fig1. Working Principle Map of Vehicles Regenerative Braking Simulation System

The hydraulic regenerative braking simulation system is made up of many components. The key components of the system are the hydraulic pump, proportional relief valves, throttle valves, hydraulic accumulator and sensors. The system can simulate the influence of the change of pressure and flow rate on the movement of vehicles under the conditions of start up, acceleration, braking and driving at a constant speed. The working principle is shown in Fig. (1).

The initial lowest pressure of the accumulator being P1, the highest P2.The pressure sensor is attached to the export of the hydraulic accumulator to detect the hydraulic accumulator pressure value and send it to the controller, which makes an electrical current signal controlling the energizing and outage of the directional valve. And that can simulates the working state of the vehicle.

1) A phase: working state of vehicle energy recovery

The electro-hydraulic proportional throttle valve, relief valve and electromagnetic directional valve produce the electromagnetic force proportional to the current signal generated by the controller, which drives the valve core movement, outputting the system pressure, and liquid flow proportional to the current signal to achieve the linear control.

In the process of the simulation of the working state of energy recovery, the pump charges the hydraulic oil from the tank into the accumulator through the opened electromagnetic directional valve after receiving the signal. When the accumulator reaches the maximal working pressure, the proportional relief valve makes the hydraulic oil overflow into the tank by the relief valve and the accumulator cannot recover the brake energy.

2) B phase: working state of vehicle energy release

The principle of vehicle energy release is similar to that of vehicle energy recovery, while what the controller deals with is another group of valves and the corresponding valve core movement of the electromagnetic proportional throttle valve and relief valve. Thus, the hydraulic oil flows into the fuel tank or low pressure accumulator from the high pressure accumulator simulating the working state of energy release.

3) C-phase: Stop of work

The pressure and flow rate do not change when the vehicle moves at a constant speed or stops, and the controller returns to the judgment of the working state of the system.

III. SIMULATION AND ANALYSIS

A. Mathematical Model

The main components affecting the performance of the system are the electro-hydraulic proportional valves, accumulator and electromagnetic directional valve. We will combine them and make an analysis from the perspective of system as a whole.

The valve is mainly formed by an armature, a coil, a spool, and a spring. The magnetic field strength is changed through the armature by adjusting the current in the coil. Then the position of the armature is changed under the effect of the resultant of the electromagnetic force and the spring force. Pushed by the armature, the movements of the spool are then regulated by the opening of the solenoid valve which directly adjust the pressure.

Solenoid modeling, the solenoid model that consists of an electrical and magnetic circuit has to handle the transformation of the input voltage to an electromagnetic force on the spool of the valve. The electrical circuit is the actual coil which is represented with a variable inductance in series with a resistance of the coil. The voltage acting on the solenoid is corresponding to the control signal [4].

$$u_0(t)-u_b(t)=i(t)R+L_c\frac{di(t)}{dt} \quad (1)$$

$$u_b(t)=K_b\frac{dx_e(t)}{dt} \quad (2)$$

where,

---the control voltage,

---the back emf,

---the coil current,

---the resistance of the coil,

---the variable inductance,

---the back electromotive coefficient,

---the displacement of the spool

But, for simplicity and conciseness of the equation, valve leakage, compressibility of the oil ,and the back emf are neglected.

The proportional amplifier forming the deep current negative feedback can be regarded as the proportion relationship. And the output voltage has good linear relationship with the given voltage.

$$u_{if}(t)=K_{fi}i(t) \quad (3)$$

$$u_0(t)=K_e\left(u_g(t)-u_{if}(t)\right) \quad (4)$$

where,

---the feedback voltage,;

---the current negative feedback coefficient,

---the given voltage of the proportional amplifier,

---the voltage amplification factor.

By adjusting the current in the coil, the magnetic field strength is changed through the armature. The electromagnetic force in the magnetic field is,

$$F_m=K_ii(t)+K_{xe}x_e(t) \quad (5)$$

where,

---the electromagnetic force,.

---the current-force gain of the proportional electromagnet

---the spring stiffness coefficient.

Because of proportional electromagnetic valve has a horizontal displacement-force characteristics, therefore, , is a minimum.

Valve modeling the valve model consists of a mass of slide spool, compression springs, and a viscous damper under the effect of electro-magnetic and flow forces [5]-[7]. It can be represented by Newton's second law,

$$F_m = M_1 \frac{d^2 x_v}{dt^2} + B_1 \frac{dx_v}{dt} + K_1 (x_{01} + x_v) + K_s x_v \quad (6)$$

$$Q = C_d A_1 \sqrt{\frac{2(\Delta P)}{\rho}} \quad (7)$$

where,
---the spool mass,
---the viscous damping coefficient,
---the viscous damping coefficient of valve spool movement,
---the damping coefficient of the transient flow forces,.
---the spring stiffness coefficient,
--- the fluid dynamic stiffness coefficient ,
---the pre-compression of spring ,
--- the displacement of spool,
---the valve flow parameter,
---the brake fluid density,
---the flow rate through the orifice,
---the orifice area corresponding to the opening position,
--- the inlet pressures,
--- the outlet pressures,
In the above equations

The energy recovery can be regarded as an adiabatic process because the process take less than one minute. So the polytropic index is 1.4, and the compressibility of the liquid can be neglected. Then, the oil flows into or out of the accumulator is [8]

$$Q_1 = \left[\frac{V_1}{np_1}\right] \frac{dp}{dt} \quad (8)$$

$$Q_2 = -\left[\frac{p_0 V_0}{np_2{}^2}\right] \frac{dp}{dt} \quad (9)$$

where,
--- the flow rate of the fluid filled,;
--- the minimum pressure,;
---the capacity of the accumulator when the pressure is lower, and are the pre-charge pressure and volume of the accumulator.
--- the maximum pressure.

B. Simulation and Analysis

To verify the effectiveness of the system, the simulated energy recovery and release system simulation model were established according to the mathematical model in Eqs (1)–(9), based on simulation software platform Matlab/Simulink.

B.1 The simulation analysis of vehicle braking deceleration state.

Simulation of the vehicle's braking and deceleration state, namely the energy recovery condition. The Regeneration of the accumulator initial pressure being 15MPa and the solenoid valve open, the energy recovery and the regenerative accumulator's filling process are simulated. The changing curve of the pressure of the regenerative accumulator is shown in Fig. (**2**).

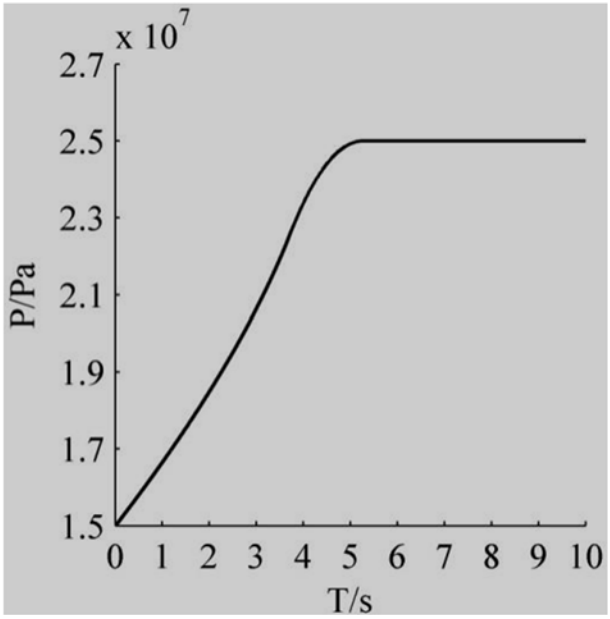

Fig2. The Pressure Change Curve of the Regenerative Accumulator

It can be seen from the figure above that the linear control characteristic of the pressure curve in the liquid filling process is obvious, and it reflects more accurately the dynamic response characteristics of the simulation system, achieving the simulation of energy recovery.

B.2 The simulation analysis of vehicle starting and accelerating conditions

Simulation of the vehicle starting and accelerating, namely energy release.

The upper pressure limit of the regenerative accumulator P2 being 25MPa, and the simulation continues until the lowest pressure reaches 15MPa.The pressure change curve of the regenerative accumulator is shown in Fig. (3).

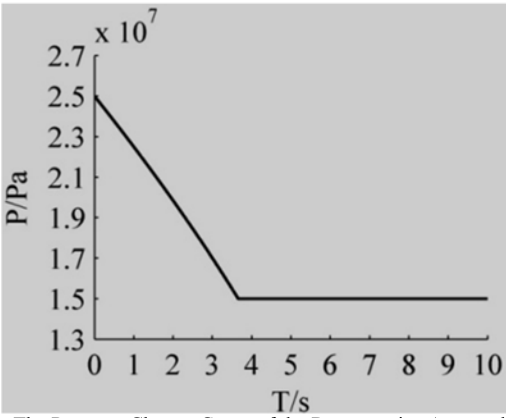

Fig3. The Pressure Change Curve of the Regenerative Accumulator.

From the figure above, we can know that the linear control characteristic of the pressure curve in the liquid releasing process is obvious, and it reflects more accurately the dynamic response characteristics of the simulation system, achieving the simulation of energy recovery.

B.3 Different pre-compression of spring simulation analysis

Setting the solenoid valve pre-compression of spring to 3mm, 5mm and 7mm respectively, and the pressure response curve of the accumulator is shown as Fig. (**4**). As the pre-compression of spring increases, the accumulator pressure will decrease and pressure response time will become longer.

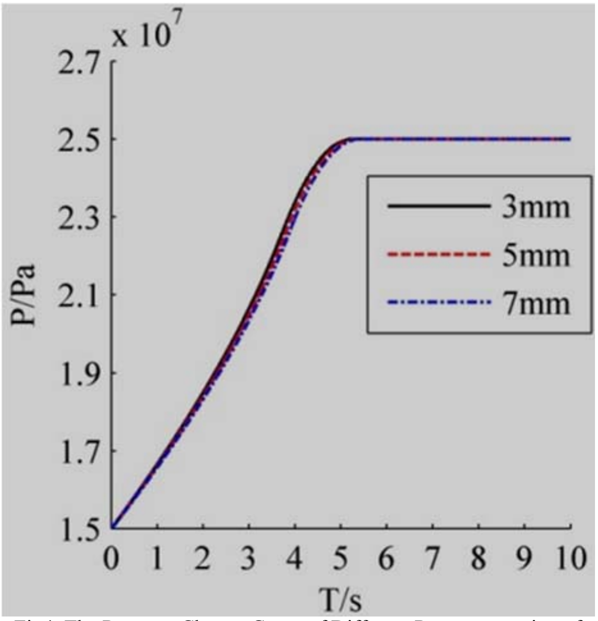

Fig4 .The Pressure Change Curve of Different Pre-compression of Spring.

IV. TEST BENCH AND EXPERIMENT VALIDATION

It is indispensable to carry out the test bench during the experiments for validating the proposed design method (Fig. (**5**)). It aims to meet the requirements of GB/T211 52-2007/ISO 3450,1996 test standard through the test bench system for reasonable layout and commissioning. The correctness of the simulation model can be verified through testing the energy recovery process under different initial low pressures and energy release process under different initial high pressures.


a) The control system b) Accumulator


c) The main test bench

Fig5. Photograph of the Test Bench.

A. Test Verification

In the process of simulating energy recovery, the inlet valve is open and the outlet valve is closed. The motor drives the pump to fill the accumulator with hydraulic oil under pressure of 10Mpa-20Mpa, 12Mpa-20Mpa and 15Mpa-20Mpa respectively. The changing curves of pressure of the accumulator under the three circumstances are recorded respectively as showed in Fig. (6).

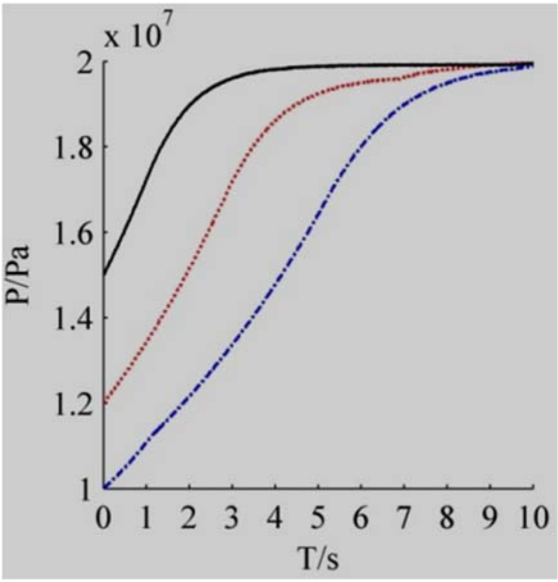

Fig6. Changing curves of pressure under three different initial low pressures.

In the process of simulating energy release, at first, the inlet valve is open and the outlet valve is closed. Then, release the oil from the accumulator until the pressure is decreased to 10Mpa.The changing curves of pressure of the accumulator under the three circumstances are recorded respectively as showed in Fig. (7).

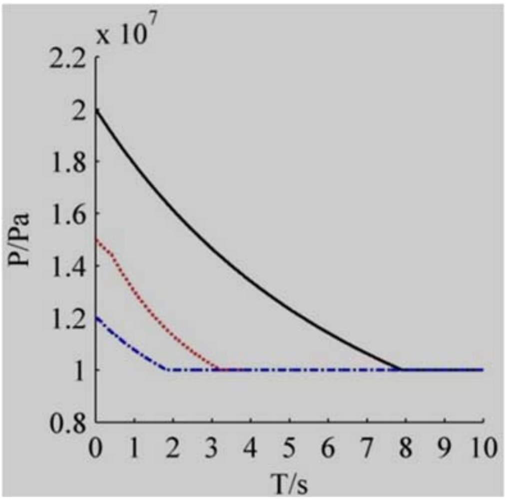

Fig7.Changing curves of pressure under-three different initial high pressures

As Fig.(6) shows, the lower the initial pressure is, the longer it takes to reach the same energy level and the recovery rate gradually becomes slowly in the energy recovery process. Likewise, seen from Fig.(**7**), the lower the initial pressure is, the quicker it is to reach the same energy level in the energy release process, and the release rate slows down. The test system is a good simulation of the system dynamic response under different conditions in line with the actual situation and can be used to simulate vehicle braking deceleration, starting and accelerating, which corresponds to the typical working conditions of energy recovery and release.

B. The Simulation and Experimental Contrast

The experiment brings the pressure curve under two typical conditions compared with the simulation curve of the mathematical model under corresponding conditions, which verifies the correctness of the model of brake energy recovery and release, and lays the foundation for the subsequent implement of hardware in loop.

B.1 Simulation and test analysis of vehicle braking deceleration

The initial pressure (P1) of the regenerative accumulator is 15.3MPa, and upper pressure limit (P2) 25MPa.

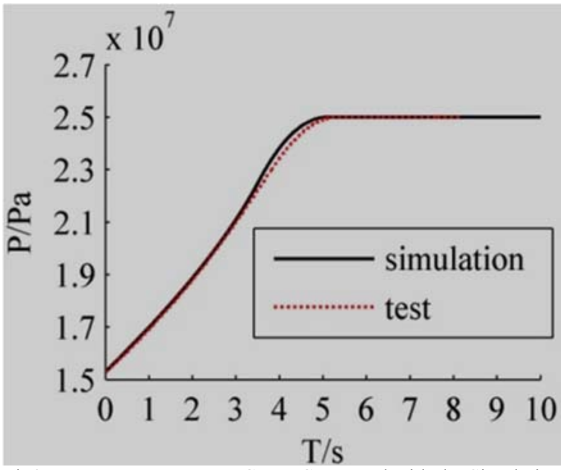

Fig8.Energy Recovery Test Curve Compared with the Simulation Curve.

Keeping the solenoid reversing valve always open ,input voltage signals-9V to the proportional throttle valve and-6V to the proportional relief valve through PCI1723,and rise the regenerative accumulator pressure to and keep it at 15.3Mpa Meanwhile, input the voltage signal-9V to the proportional relief valve and record the changing curve of pressure of the accumulator by HMG3000 handheld tester. The simulation curve is compared with the test curve, as shown in Fig. (8).

It can be seen from the figure that the simulation curve is similar to the experimental curve, and the linear control characteristic is obvious. The regenerative accumulator pressure reaches the upper limit-25MPa in about 5.5s, which can more accurately reflect the dynamic response characteristics of the simulation system to realize the simulation process of energy recovery.

B.2 Simulation and test analysis of vehicle starting and accelerating

The inlet valve open, voltage signal-9V is input to the proportional relief valve with the upper limit (P2) of the pressure of the regenerative accumulator-25Mpa and the solenoid valve is closed when the pressure reached 25Mpa. The outlet valve open while other valves closed in the experiment, the voltage-9V is input to the proportional relief valve and the proportional throttle valve. The outlet valve is closed when the accumulator pressure drops to 15Mpa with the oil release rate controlled by the throttle valve，The simulation curve is compared with the test curve, as shown in Fig .(9).

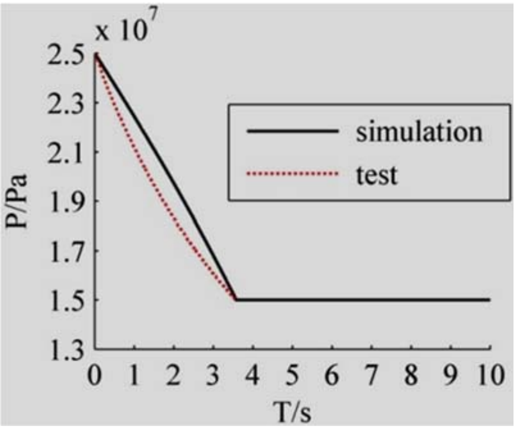

Fig.9. Energy Release Test Curve Compared with the Simulation Curve.

Seen from the figure above, the simulation curve is similar to the experimental curve, and the linear control characteristic is obvious. The regenerative accumulator pressure reaches the limit 15MPa in about3.5s. It can more accurately reflect the dynamic response characteristics of the simulation system, achieving the simulation process of energy release.

V. CONCLUSION

A new type of vehicle hydraulic regenerative braking simulation system is designed through comparing different vehicle hydraulic hybrid test systems and analyzing the advantages and disadvantages of their structures.

The system simulation models of braking energy recovery and release are established. The dynamic characteristics of the system in the processes of charging and discharging are simulated, which is similar to the actual situation.

Different test conditions of energy recovery and release processes are simulated and two typical vehicle energy recovery and release processes are tested, verifying the roughly identity between the test curve and the simulation curve, the universal applicability of the designed simulation test bench and the validity of dynamic system design method.

This paper provides the basis for the design of the vehicle regenerative braking simulation system and lays the foundation for the success of subsequent experiments of hardware in loop under various conditions.

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REFERENCES

[1] HEWKO L O, WEBER T R, “Hydraulic energy storage based hybrid propulsion system for a terrestrial vehicle,” Proceedings of the Intersociety Energy Conversion Engineer- ing Conference, Reno, NV,USA, pp.99-105,1990.

[2] Lynn A., Smid E., Caldwell N, “Modeling hydraulic regener -ative hybrid vehicle using AMESim and Matlab/Simulink,” Proceedings of SPIE-The International Society for Optical Engineering, Rochester Hills, MI, USA,pp.24-40., 2005.

[3] Frank A. Bender, Martin Kaszynski, Oliver Sa-wodny," Drive cycle prediction and energy management optimization for hybrid hydraulic vehicles," IEEE Transactions on vehicular technology, vol.62, pp.3581-3592,October 2013.

[4] Gamble, J.B., Vaughan, N.D., "Comparison of sliding mode control with state feedback and PID control applied to a proportional solenoid valve". Proceedings of the 1994 Inter-national Mechanical Engineering Congress and Exposition, Chicago, IL, USA,pp.51-58,, 1994.

[5] Jin Bo, Zhu Yaguang, "A differential control method for the proportional directional valve," Journal of Zhejiang University: Science C, vol.15, pp.892-902，October，2014.

[6] Kuang,M.L Fodor,M, Hrovat,M, Tran,M, "Hydraulic brake system modeling and control for active control of vehicle dynamics," Proceedings of the 1999 American Control Confer-ence, San Diego, CA, USA, pp.4538-4542,1999.

[7] Mingchin Wu , Mingchang Shi," Simulated and experiment-al study of hydraulic anti-lock braking system using sliding-mode PWM control," Mechatronics, vol.13, pp.331-351,May,2003.

[8] Jing Li, and Xi Zhang, "Dynamic Temperature Simulation of an Accumulator in Aircraft Hydraulic Systems". 2011 International Conference on Fluid Power and Mechatronics, FPM 2011, Beijing, China,pp. 653-657,2011.