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RESEARCH OF A NEW ENERGY RECYCLING ELECTRO-HYDRAULIC CONTROL SYSTEM BASED ON HIGH SPEED ON/OFF VALVES

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ABSTRACT

Compared with mechanical transmission, hydraulic systems have advantages of larger power density, wider range of speed regulation, and easier realization of overload protection. However, energy efficiency of traditional hydraulic systems is only about 30% due to throttle loss and spill loss. In order to increase capacity usage ratio, a new energy recycling electro-hydraulic control system (ERECS) is studied in this paper. Firstly, the scheme of ERECS is stated. A 2-position 3-way high speed ON/OFF valve together with a large flow rate 2-way cartridge valve acting as a valve-group with little throttle loss and spill loss is discussed. Secondly, simulation models of position control system and force control system based on the valve groups are established in AMESim and control program is written in Simulink. Thirdly, after setting parameters of these two models, the step signal and sinusoidal signal responses for two models respectively are performed to test the force and displacement control performance. Finally, further analysis testifies the efficiency of the ERECS which can reach up to 75% in a given case. This paper has proved that the ERECS can ensure control performance to some degree and improve energy efficiency largely at the same time.

KEYWORDS: energy recycling electro-hydraulic control system (ERECS), energy recycling, high speed ON/OFF valve, position control, force control, efficiency

1 INTRODUCTION

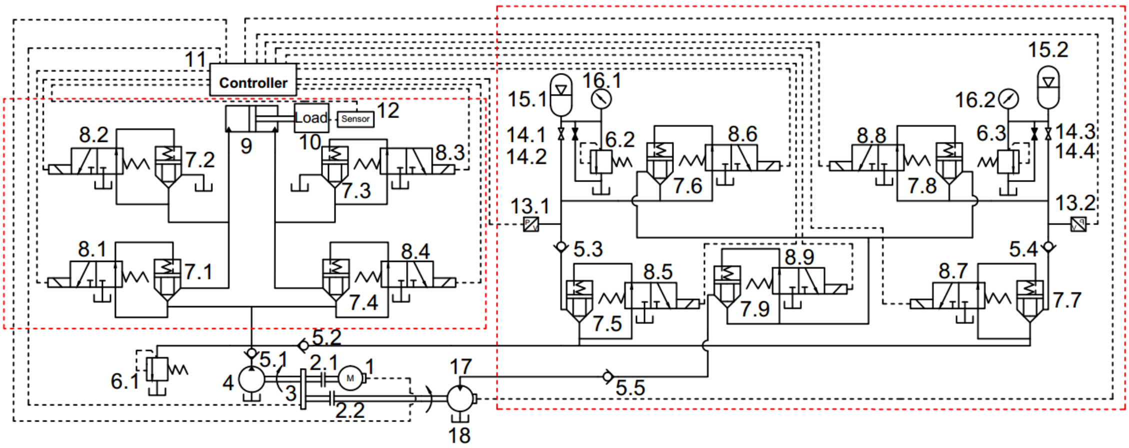
In general, hydraulic systems have advantages of larger power density, wider range of speed regulation, and easier realization of overload protection compared with other common mechanical systems [1] [2]. The traditional hydraulic systems contain lots of overflow valves and proportion valves to obtain above properties. However, all these valves have throttle orifices which will cause throttle loss and spill loss. Energy losses concerning throttle loss and spill loss account for huge proportion in traditional hydraulic systems [3] [4]. Consequently, energy efficiency of traditional hydraulic systems is only about 30% [5]. Many researchers put forward some methods to improve the efficiency of traditional hydraulic systems [6] [7] [8]. However, throttle loss and spill loss still can't be ignored. In order to increase capacity usage ratio in traditional hydraulic systems, a new energy recycling electro-hydraulic control system (ERECS) is put forward and studied in this paper. ERECS almost without throttle orifices, as a result, can nearly eliminate throttle loss and spill loss. At the same time, this system can still ensure positional control accuracy and force control accuracy to some degree.

This paper consists of four sections: scheme of ERECS, position control and force control of ERECS, efficiency of ERECS, conclusion.

2 SCHEME OF ERECS

2.1 Working mechanism of ERECS

The schematic diagram of ERECS is presented as below (seeing Fig.1). According to the schematic diagram, this system mainly contains two subsystems: valve control cylinder subsystem (red percentage in the left side of Fig.1) and energy recycling subsystem (red percentage in the right side of Fig.1).



1-Motor 2-Coupling 3-Differential mechanism 4-Hydraulic pump 5-One-way valve 6-Overflow valve 7-Cartridge valve 8-High speed ON/OFF digital valve 9-Hydraulic cylinder 10-Load 11-Controller 12-Displacement or force senor 13-Pressure sensor 14-Ball valve 15-Accumulator 16-Piezometer 17-Hydraulic slave motor 18-Tank

Fig.1 The scheme of ERECS

Firstly, in the valve control cylinder subsystem, a 2-position 3-way high speed ON/OFF valve together with a large flow rate 2-way cartridge valve acts as a valve-group with little throttle loss and spill loss. Four valve-groups are used to control the movement of a hydraulic cylinder, which can act as a closed loop position control system or a closed loop force control system.

Secondly, energy recycling subsystem mainly contains two accumulators and five valve-groups to collect hydraulic energy when all the two-position three way high speed ON/OFF valves of valve control cylinder subsystem are in the right place. At the same time, recovered energy is utilized to drive a hydraulic motor 17 which can provide a torque for the motor 1.

To explain the ERECS smoothly with examples, this paper gives below definition.

If valve 7.1 is closed, we claim that valve-group 7.1 & 8.1 is closed. On the contrary, if valve 7.1 is open, we claim that valve-group 7.1 & 8.1 is open. This definition is suit for valve-groups 7.2 & 8.2, 7.3 & 8.3, 7.4 & 8.4, 7.5 & 8.5, 7.6 & 8.6, 7.7 & 8.7, 7.8 & 8.8, and 7.9 & 8.9.

When valve-groups 7.1 & 8.1 and 7.3 & 8.3 are open and valve-groups 7.2 & 8.2 and 7.4 & 8.4 are closed, the piston rod of hydraulic cylinder 9 extends. But if valve-groups 7.1 & 8.1, 7.3 & 8.3, 7.2 & 8.2 and 7.4 & 8.4 are all closed, the piston rod of hydraulic cylinder 9 keeps still. So the piston rod can extend or keep still by turns. If the time span to extend is controlled properly just like pulse-width modulated digital control system [9], ultimately, the piston can arrive the ideal position or output ideal propulsive force. During this alternate process, valve-group 7.5 & 8.5 is open and valve-groups 7.6 & 8.6, 7.7 & 8.7, 7.8 & 8.8, 7.9 & 8.9 are closed firstly. We utilize accumulator 15.1 to collect hydraulic energy when four valve-groups of valve control cylinder subsystem are all closed. If 15.1 collects enough energy, it is time to open valve-groups 7.9 & 8.9, 7.6 & 8.6, 7.7 & 8.7. At the same time accumulator 15.1 releases the collected energy to drive hydraulic slave motor 17. Meanwhile, 15.2 can collect hydraulic energy just like 15.1. During this process, the piston rod moves towards the right.

When valve-groups 7.2 & 8.2 and 7.4 & 8.4 are open and valve-groups 7.1 & 8.1 and 7.3 & 8.3 are closed, the piston rod of hydraulic cylinder 9 retracts. When valve-groups 7.1 & 8.1, 7.3 & 8.3, 7.2 & 8.2 and 7.4 & 8.4 are all closed, the piston rod of hydraulic cylinder 9 will keep still. So the piston rod can retract or keep still by turns. If the time span to retract is controlled properly, the piston can arrive the ideal position or output ideal pulling force ultimately. During this alternate process, valve group 7.5 & 8.5 is open and valve-groups 7.6 & 8.6, 7.7 & 8.7, 7.8 & 8.8, 7.9 & 8.9 are closed firstly. We utilize 15.1 to collect hydraulic energy when the four valve-groups of valve control cylinder subsystem are all closed. If 15.1 collects enough energy, it is time to open valve-groups 7.9 & 8.9, 7.6 & 8.6, 7.7 & 8.7. At the same time 15.1 releases the collected energy to drive 17. Meanwhile, 15.2 can collect hydraulic energy just like 15.1. During this process, the piston rod moves towards the left.

By means of differential mechanism 3, it does not matter whether the speed of 17 is equal to the speed of 1 or not. In a word, the torque driving 4 is the sum of the torque of 1 and the torque of 17. In this situation, power dissipation of 1 will be much less, because the recovered energy from energy recycling subsystem can be taken advantage of by the valve control cylinder subsystem.

2.2 Method of designing the valve group

In this section, the simulation models of valve-groups are established in AMESim and their parameters are given at the same time.

Poppet with sharp edge seat, mass with friction and ideal end stops, and piston with spring constitute the large flow rate 2-way cartridge valve. This 2-way cartridge valve as well as a 2-position 3-way hydraulic valve forms the valve group in AMESim (seeing

Fig.2). All these sub-models can be found in AMESim. We just need to assemble them together.

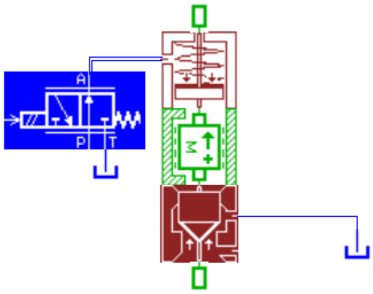


Fig.2 Model of the valve group

More difficult task is to set the parameters of those sub-models. Some basic principles must be satisfied. When the 2-position 3-way hydraulic valve in Fig.3 is in the right position,

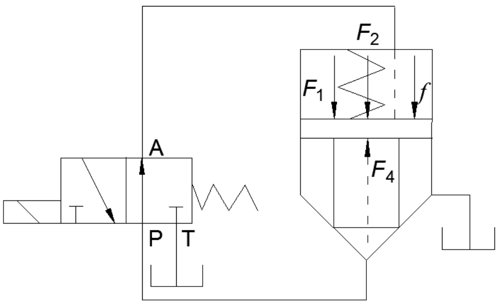
$$F_4 < F_1 + F_2 + f \tag{1}$$

On the contrary, when the 2-position 3-way hydraulic valve in Fig.3 is in the left position,

$$F_4 \gg F_2 + f \tag{2}$$

In this situation,

$$F_1 = 0 \tag{3}$$



F_1-Pressure of hydraulic oil F_2-Force of spring f-Friction force of spool

F_4- Joint forces of boosting the spool up

Fig.3 Simplified figure of valve group

To set the parameters of those sub-models of this valve group properly, the inner equations of the poppet with sharp edge seat need to be studied. To figure out the inner equations of the poppet with sharp edge seat, a figure of inner variables of conical poppet valve and a simplified geometric figure of conical poppet valve will help us a lot (seeing Fig.4 and Fig.5).

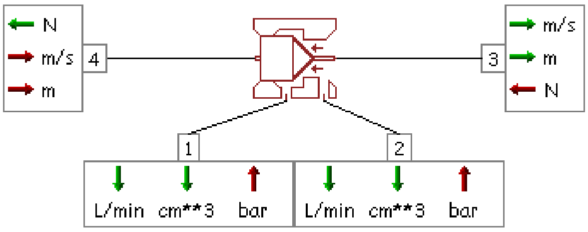
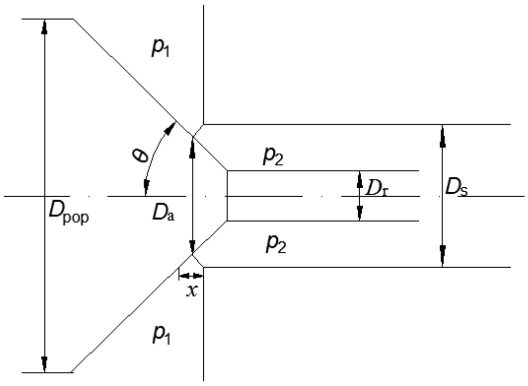


Fig.4 Inner variables of conical poppet valve



p_1-Pressure of port 1 p_2-Pressure of port 2 D_{pop}-Diameter of poppet

D_s-Diameter of hole D_r-Diameter of rod (seat side)

θ-The jet angle of liquid

Fig.5 Simplified geometric figure of conical poppet valve

According to Fig.4 & Fig.5, the force of port 4 is:

$$F_4 = F_3 - F_{\mathrm{jet}} + \frac{\pi}{4} P_1 \left(D_{\mathrm{pop}}^2 - D_{\mathrm{a}}^2 \right) + \frac{\pi}{4} P_2 \left(D_{\mathrm{a}}^2 - D_{\mathrm{r}}^2 \right) \tag{4}$$

This is an algebraic equation, not vector equation. Where F_4 represents joint forces of boosting the spool up.

$$D_{\mathrm{a}} = D_{\mathrm{s}} - 2x \sin\theta \cos\theta \tag{5}$$

Where F_3 represents the force of port 3(seeing Fig.4). In this paper, we set F_3 as zero to simplify our task without reducing the simulation accuracy. Where F_{jet} represents the steady state axial flow force in the conical poppet valve. This force tends to close the conical poppet valve. For steady state flow of a liquid, the flow force F_{jet} is evaluated by:

$$F_{\mathrm{jet}} = k_{\mathrm{jet}} \left(\tanh \frac{2(x_{\mathrm{lap}} - x_{\mathrm{min}})}{x_{\mathrm{min}}} + 1 \right) c_{\mathrm{q}} a \Delta p \cos\theta \tag{6}$$

$$a = \pi x \sin\theta \left(D_s - x \sin\theta \cos\theta \right) \qquad (7)$$

Where x_{min} represents spool displacement of the conical poppet valve when the flow area of the conical poppet valve is minimum. Where x_{lap} represents valve opening of the conical poppet valve when the displacement of port 3 of the conical poppet valve is zero. Where c_q is flow coefficient and a is flow area. And dp is pressure drop. Where k_{jet} represents jet forces coefficient.

According to above equations and expound, we give below parameters directly (seeing table 1).

Table 1 Parameters of models

Poppet valve	diameter of poppet	0.040m
	diameter of hole	0.030m
	diameter of rod (seat side)	0.005m
	poppet half angle	45degree
	spool displacement for maximum area	0.006m
Mass	mass	0.05kg
	static force	10N
	inclination	0degree
	higher displacement limit	0.007m
	lower displacement limit	0m
Piston with spring	piston diameter	0.060m
	rod diameter	0.005m
	spring force at zero compression	10N
	spring stiffness	10N/m
	chamber length at zero displacement	0.007m
	spring compression at zero displacement	0m
Overflow valve	relief valve cracking pressure	28MPa

2.3 Model of ERECS

After above work, the simulation models of position control system and force control system are established in AMESim. Fig.6 is the simulation model of position control system. Fig.7 is the simulation model of force control system. They are identical except the connector between the hydraulic cylinder and load. In the force control system, to avoid rigid contact which can cause the fluctuation of the force, a spring is added between hydraulic cylinder and rigid body. In the position control system, rigid contact is reasonable.

Interfaces of these two models are also established in AMESim for sake of programming in Simulink. The working mechanisms of these two models has been explained in section one.

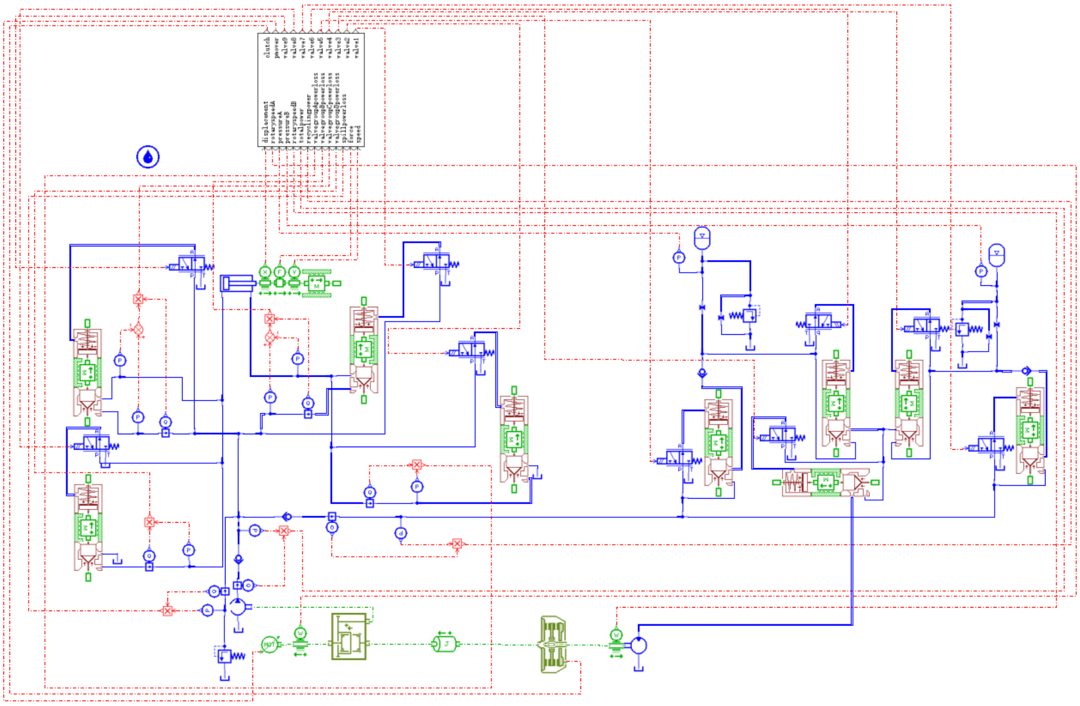


Fig.6 Simulation model of position control system

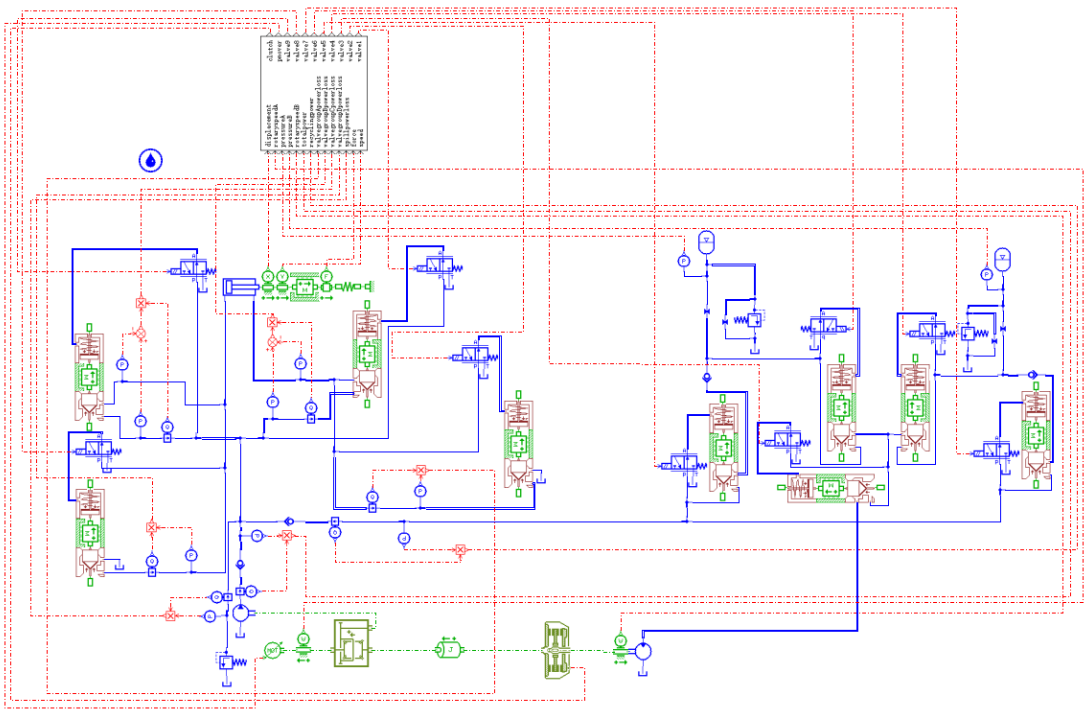


Fig.7 Simulation model of force control system

3 POSITION CONTROL AND FORCE CONTROL OF ERECS

3.1 Control method of ERECS

Some details need to be stated firstly. As to 2-position 3-way high speed ON/OFF valve, if 40mA current is outputted to the receiving terminal of the ON/OFF valve, the valve will stay in the left place. If 0mA current is outputted to the receiving terminal of the ON/OFF valve, the valve will stay in the right place.

According to the theory of ERECS, the control program is written in Simulink (seeing Fig.8).

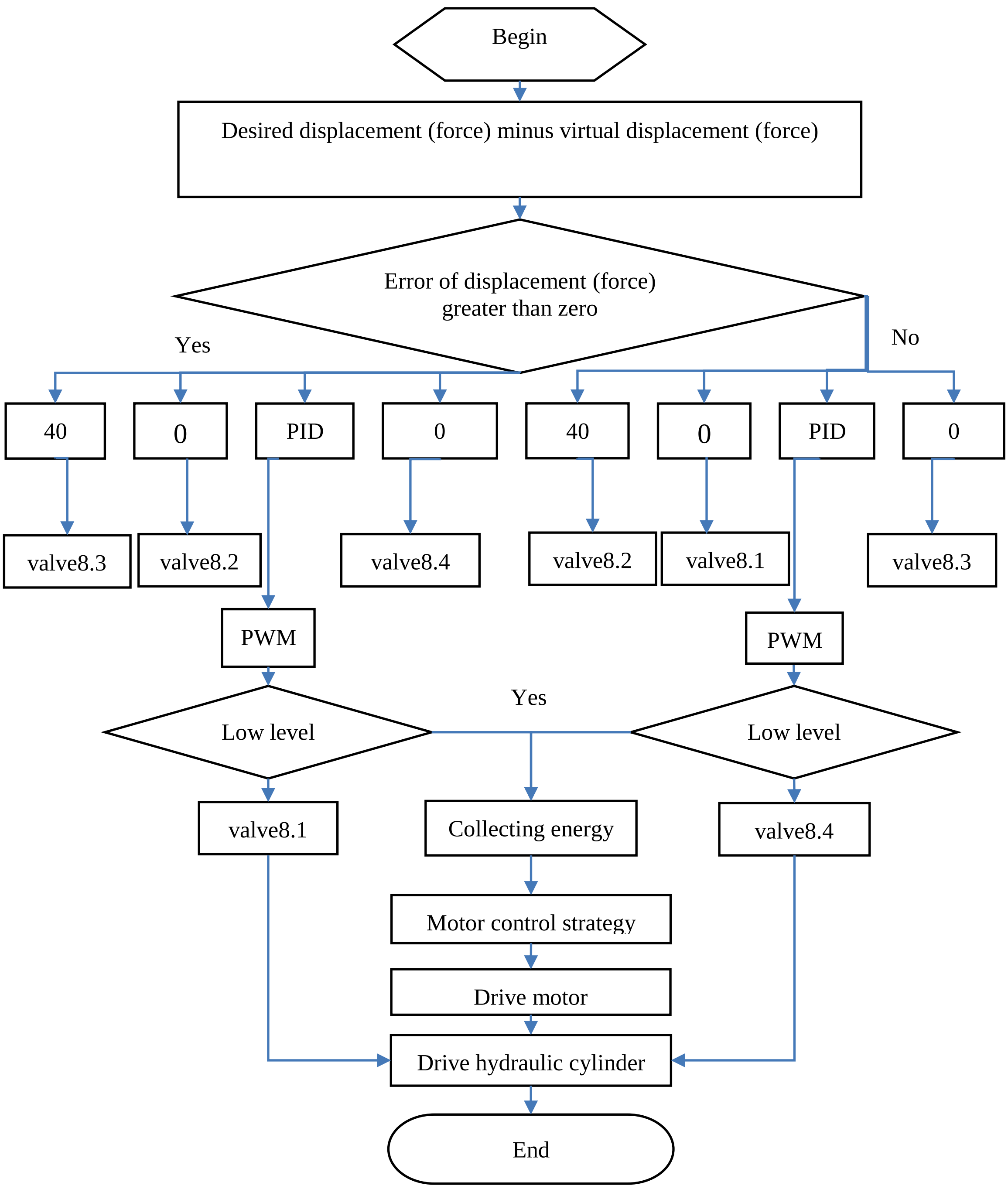


Fig.8 Control flow graph

Firstly, the controller obtains the error between desired displacement (force) and virtual displacement (force). According to the size of the error, the controller decides how to control different valves (seeing Fig.8). For example, if the virtual displacement is smaller than desired displacement, the controller will output corresponding values to different valves to make the piston rod of cylinder move right. If the virtual displacement is bigger than desired displacement, the controller will output corresponding values to different valves to make the piston rod of cylinder move towards the left.

PID outputs a value which is between 0 and 1. That value is duty cycle of a square wave which is between 0 and 40. The bigger the value is, the longer the time span of extending or retracting the piston rod of the cylinder is. When the displacement or force arrive the ideal value, the output of the PID is zero. Controlled by the controller, the energy recycling subsystem collects hydraulic energy when the square wave stays in low value.

3.2 Position control of ERECS

A step signal as ideal position signal is given to the controller at first. The controller detects the actual displacement using displacement sensor and acquires the error between ideal displacement and this actual displacement. According to the size of this error, the controller controls corresponding valve groups. Fig.9 shows the result of controlling the cylinder to follow the trail of an ideal step displacement. Fig.10 shows the result of controlling the cylinder to follow the trail of an ideal sine displacement. From Fig.9 & Fig.10, the displacement accuracy is not bad.

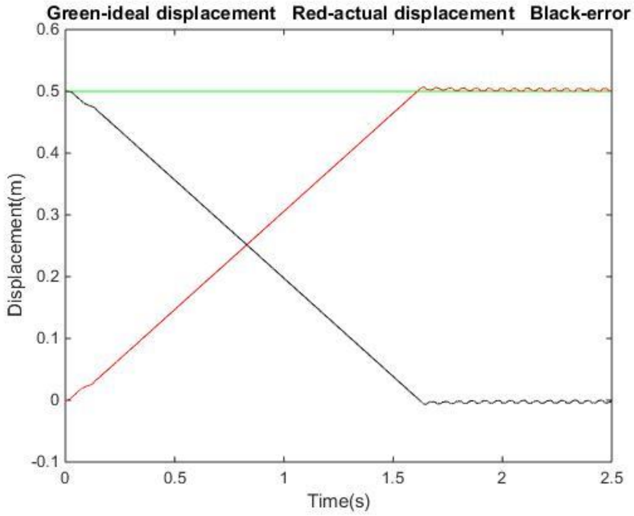


Fig.9 Step position control of ERECS

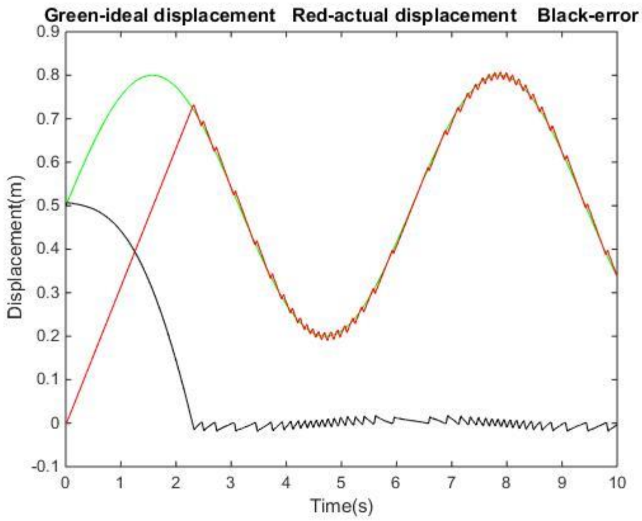


Fig.10 Sine position control of ERECS

3.3 Force control of ERECS

A step signal and a sine signal as ideal force signals are given to the controller respectively to testify the force control property of the ERECS. Taking a step signal for example, the controller detects the actual force using force sensor and acquires the error between ideal force and this actual force. According to the size of this error, the controller controls corresponding valve groups. Fig.11 shows the result of controlling the cylinder to follow the trail of an ideal step force. From Fig.11, the accuracy of the force is acceptable. Fig.12 shows the result of controlling the cylinder to follow the trail of an ideal sine force. According to Fig.12, actual force can tail after ideal sine force to some degree.

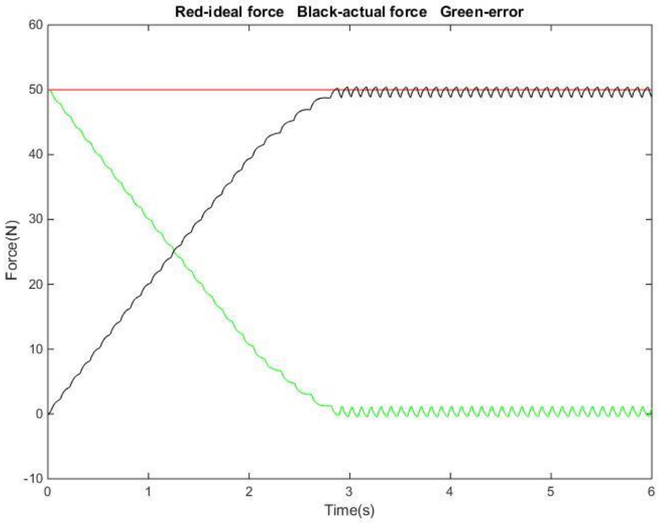


Fig.11 Step force control of ERECS

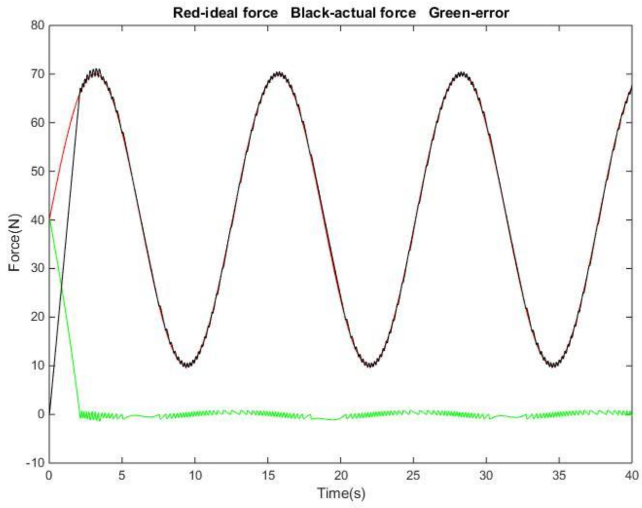


Fig.12 Sine force control of ERECS

4 THE EFFICIENCY OF ERECS

To testify the energy efficiency of the ERECS, we let the ERECS tail after ideal sine displacement and detect the power used in different aspects of this system (seeing Fig.13 & Fig.14).

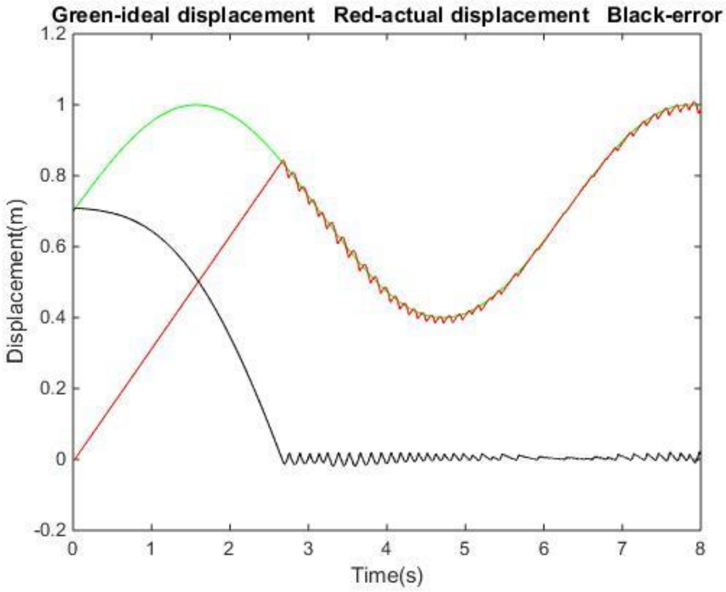


Fig.13 Sine position control of ERECS

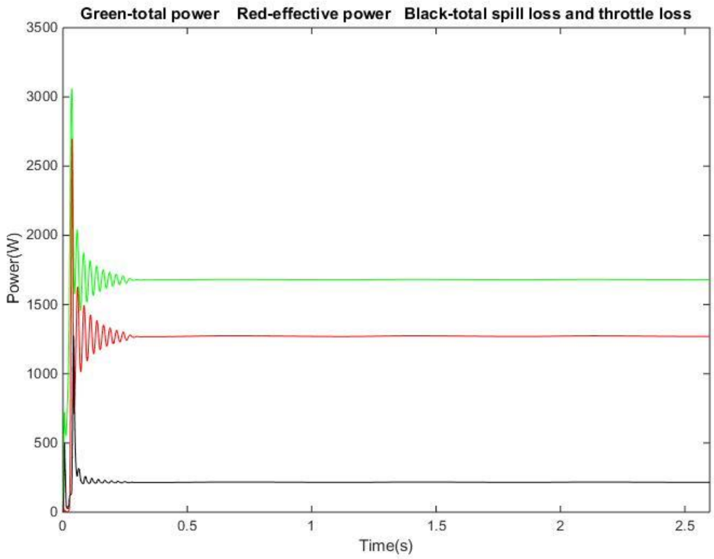


Fig.14 Power used in different aspects of this system

According to Fig.14 & Fig.13, the ERECS can ensure control performance to some degree and improve energy efficiency largely at the same time. In this given situation, the efficiency of the system can reach up to 75%. Through simulations, the pressure drop of valve groups is no more than 0.5MPa even though the pressure at the inlet of the valve large flow rate 2-way cartridge valve is over 20MPa.

5 CONCLUSION

To sum up, a new energy recycling electro-hydraulic control system (ERECS) is discussed in this paper in detail. By analysis at length, the simulation models of position control system and force control system are established in AMESim. Then PID control program is used to control these two models.

According to above results, the pressure drop of valve groups of ERECS is far less than that of proportional valves and solenoid valves which are in common use in traditional hydraulic systems. So the energy loss concerning throttle loss and spill loss can be ignored or in small proportion in this new hydraulic system. This kind of energy loss is the primary part of all energy loss in traditional hydraulic systems. Therefore, the efficiency of ERECS can be improved largely compared with that of traditional hydraulic systems. In a given situation, the energy efficiency of the ERECS can reach up to 75%.Through proper control algorithm, such as PID in this paper, this new system can acquire excellent position accuracy and force accuracy to some degree. Of course, this system have some shortcomings which need to be overcome still. For instance, during opening or closing the high speed ON/OFF valves, the system vibrates a little. At the same time, some optimized algorithms which are used to control the ERECS need to be studied. By means of these optimized algorithms, the ERECS can offer the recovered energy to the valve control cylinder system efficiently. In fact, if the energy recycling system can’t release the recovered energy reasonably, the energy saving property of ERECS will be discounted.

6 ACKNOWLEDGEMENT

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