Research on the Characteristics of Electro-hydraulic Proportional Steering System in Self-Propelled Modular Transporter

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***Abstract*—According to the steering mode of self-propelled modular transporter, the key component of the steering system with electro-hydraulic proportional directional valve was designed. The model of the transporter steering single loop system was established through the method of power bond graph and was simulated. The dynamic characteristics of steering circuit were analyzed. Results indicate that the system has good steering stability and dynamic response.**

***Keywords*—self-propelled modular transporter, electro-hydraulic proportional valve, power bond graph, simulation, dynamic characteristics.**

I. INTRODUCTION

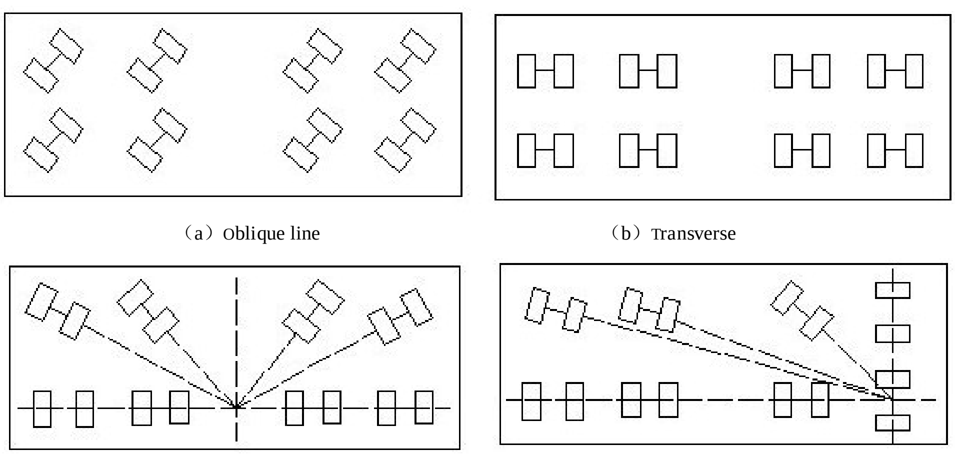
The self-propelled modular transporter(SPMT) is multiple axis vehicle which has various steering model such as straight, oblique line, transverse, spin. The operation, stability and security of the SPMT depend on its steering performance in the process of working [1]. A single SPMT has either six or four axle lines, with each axle line consisting of four wheels arranged in pairs. Each pair of wheels can pivot 360°about its support point. The SPMTs can be rigidly coupled longitudinally and laterally to form multiple units. The traffic safety is influenced If the design of SPMT steering system is unreasonable which can cause mutual influence between different tire angle [2]. Electro-hydraulic proportional control system is widely used in multi-axis tyred vehicle which has high control precision, rapidity and stability compared with the traditional switch control system [3]. The steering system of SPMT can effectively perform its straight, oblique line, and spin various steering modes with strong anti-pollution ability, high stability of steering because it adopts electro-hydraulic proportional valve as the key component [4].

The factors influencing the static and dynamic characteristics of electro-hydraulic proportional directional valve were studied through establishing the model of steering system in order to improve the stability and control accuracy of steering system.

II. THE ELECTRO-HYDRAULIC PROPORTIONAL STEERING SYSTEM OF SPMT

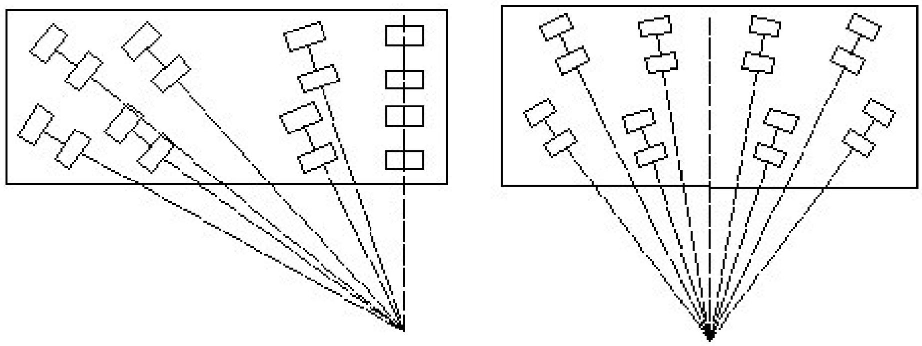
A. The analysis on steering mode

In order to ensure that the SPMT with load can close to all processes in the scene, and avoid the other equipment as well as meet the work requirements, SPMT should have be different steering modes such as straight, oblique line, transverse which make the handling of overloaded cargo safety and efficiency because the weight and volume of goods transported is very large. The steering system working mode of 150t SPMT with 4-axis is shown in figure 1.



（a）Oblique line （b）Transverse

（c）Pivot sterring （d）Front sway and wiggle-tail



（e）Steering of half sector （f）Steering of sector

Fig.1 Steering mode of four axis SPMT

The steering angle should reach to 180 °(that is angle of positive and negative steering can be to 90 °) in the steering mode of SPMT which can realize transverse moving and various steering modes. The steering mechanism with uniform speed and easy controlling is required to be stable transmission ratio, high efficiency, high reliability, big steering angle and smooth steering.

The SPMT can complete various steering modes which mainly depend on the performance of control system. If the accuracy of control system is too low, coordination movement precision between axles is reduced which result in realizing the approximate pure roll around the center of steering difficultly and making the tire wear quickly, even may lead to a rollover accident in the case of load.

B. The design of steering system with electro-hydraulic proportional control

Electro-hydraulic proportional control steering is widely used in large multi-axle steering vehicle for its large driving force, high control precision and the flexible way of energy conversion. The steering system of SPMT was designed by adopting electro-hydraulic proportional control system. This steering system is composed of three parts including driving mechanism, hydraulic system and control system. There are the instruction signal processing and amplification components, hydraulic pump, electro-hydraulic proportional valve, hydraulic motor, load, Angle sensors in steering system.(As shown in figure2.)

The hydraulic steering of SPMT with electro-hydraulic proportional control system realize the precise control of each wheel steering and tires to approximate roll by closed-loop control of each wheel rotation with angle sensor. The structure of control system is shown in figure 3.

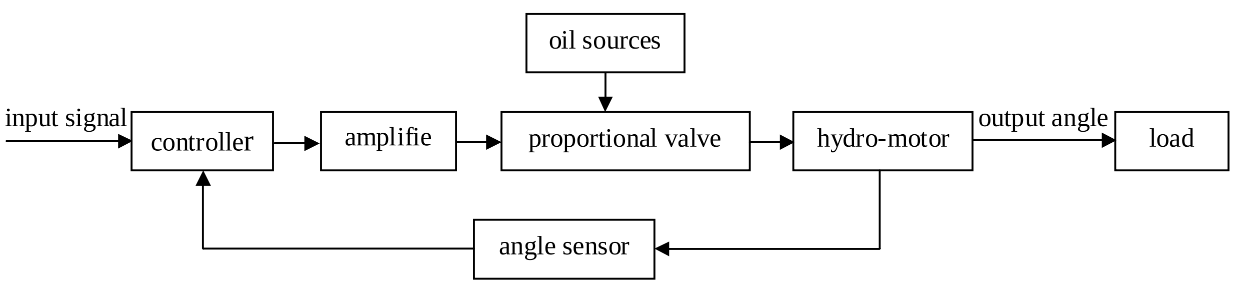


Fig. 1 Constitution of electro-hydraulic proportional control system

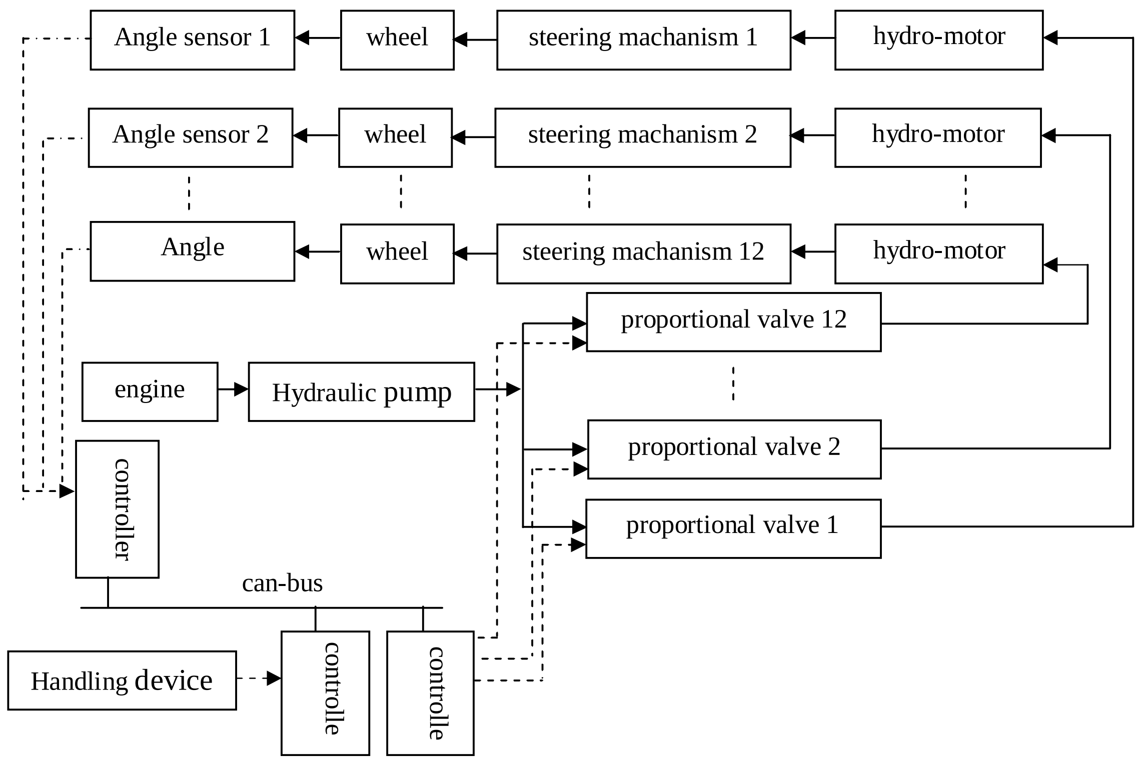


Fig.3 The steering system of SPMT

When the steering instructions of steering wheel are send, the controller adjust opening of valving element by sending control signal to proportional valve. The control signal was acquired by parsing out the expectations of each wheel angle according to the established kinematics model of vehicle steering and the input angle of steering wheel.

At the same time, the steering angle of each steering wheel was controlled by controlling the flow of hydraulic motor with electro-hydraulic proportional valve.

Angle sensor is mounted on the hydraulic motor through which the actual steering angle is feedback to the controller. The latest actual wheel angle is received by CAN bus. The output of hydraulic motor was solved. The CAN bus sends corresponding control instruction to I/O nodes in order to reduce the deviation. The process of control is cycling until the steering angle of each wheel is expected. The closed loop of the whole system can satisfy the requirement of high precision of SPMT steering system.

III. The Establishment of Electro-Hydraulic Proportional Steering System Model

A. The working process of the circuit with electro-hydraulic proportional control

The single loop system of electro-hydraulic proportional steering system of SPMT is shown in figure 4. When there is not current into the electromagnet, the reversing valve is in mid-position because each port of proportional relief pressure valve is not connected each other.

When there is current entering into the electromagnet, electro-hydraulic proportional pressure reducing valve 1 start to action and shift to the right position. The pressure Ps1 is formed when the hydraulic oil is flowed into controlling chamber of left side of reversing valve in the main hydraulic system through valve port a. At this point, the main spool of reversing valve is shifted to right position and connected to valve port PA under the pressure of Ps1 and spring force. When a certain flow of oil is entered into the hydraulic motor, the hydraulic motor drives planet gear rotating and makes wheels rotating. In the same way, when there is current entering into the electromagnet 2, electro-hydraulic proportional pressure reducing valve 2 starts to action and valve port is unlocked. The pressure Ps2 is formed when the hydraulic oil is flowed into controlling chamber of right side of reversing valve in the main hydraulic system through valve port b. The pressure Ps2 pushes main spool of reversing valve moved to left position and connected to valve port PB.

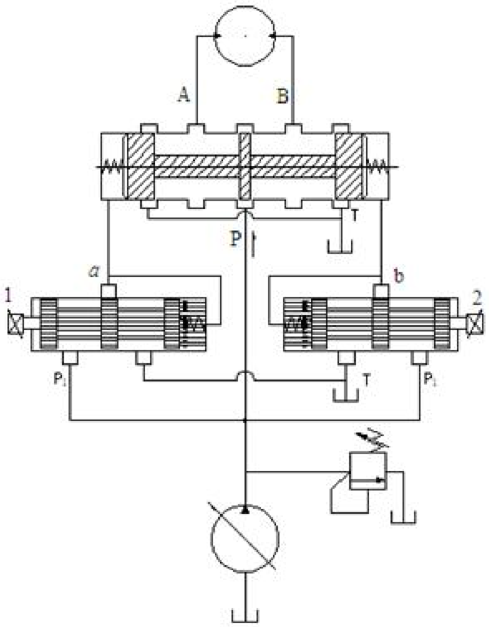


Fig.4 Simplified steering system of single axle SPMT

B. The power bond graph model of proportional steering system

Electro-hydraulic proportional control system was adopted in the steering system of SPMT. The steering system is affected by nonlinear influence factors such as the flow and pressure characteristics and oil compressibility in working process [5]. Power bond graph method is a large nonlinear system modeling method suitable for multi-input and multi-output. So the model of SPMT steering system was established by power bond graph method.

The single axis steering system of SPMT is composed of variable pump, relief valve, proportional pressure reducing valve, reversing valve and hydraulic motor, etc. In the process of modeling, leakage of the pipe joint is ignored and density, viscosity and modulus of elasticity of the oil are assumed as the ideal state that unaffected with change of pressure and temperature.

Based on components of SPMT steering system, System bond graph model is set up according with the principle of bond graph modeling [6] [7] [8]. (as shown in figure 5 ,take steering right as an example).

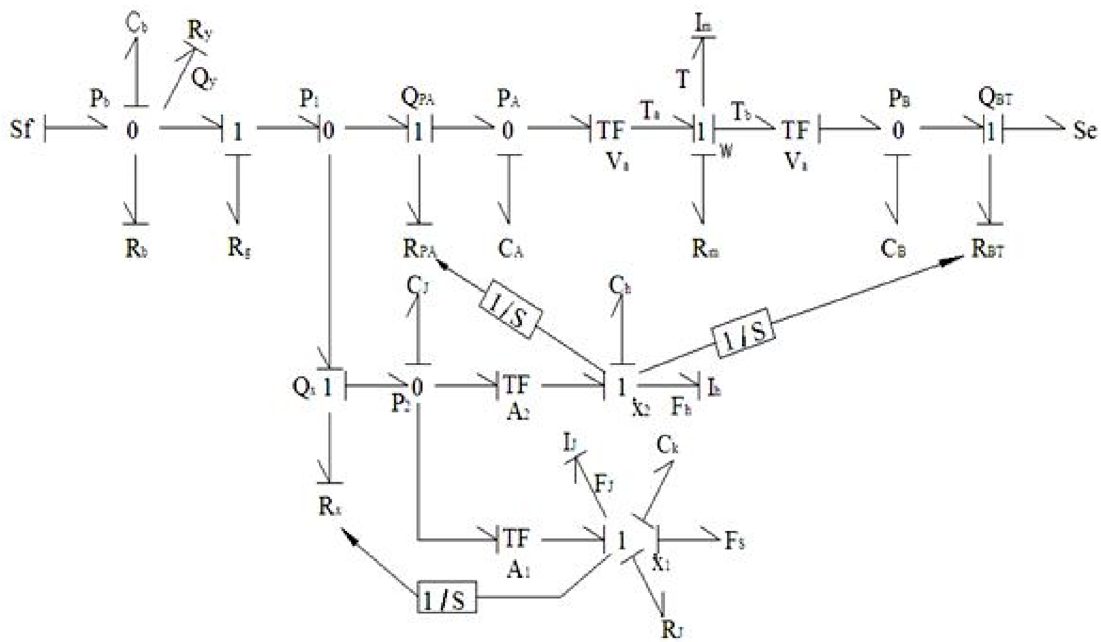


Fig.5 Power bond graph Steering mode of spool to right

The meaning of each symbolic in bond graph is as follows: S_f - source of hydraulic oil; P_b - output pressure of hydraulic pump ; C_b - hydraulic pump liquid capacity of the oil cavity; R_b - liquid resistance of hydraulic pump leakage; Ry - fluid resistance of relief valve; Q_y -overflow discharge of relief valve; R_g - fluid resistance of tube; P_1 - inlet pressure of reducing valve; P_2 - outlet pressure of reducing valve; Q_x - valve port flow of reducing valve; R_x - fluid resistance with spool openings of reducing valve; A_1 -spool area of proportional reducing valve; F_S - electromagnetic force; C_J - liquid capacity of reducing valve output chamber; C_K - spring stiffness of reducing valve; I_J -spool mass of reducing valve ; R_J - spool viscous damping coefficient of reducing valve;

X_{11} - spool displacement of reducing valve; A_2 - spool area of reversing valve; C_h - spring stiffness of reversing valve; I_h - spool mass of reversing valve; X_{12} - spool displacement of reversing valve; R_{PA} - fluid resistance of PA port of reversing valve; R_{BT} - fluid resistance of BT port of reversing valve; C_A - liquid capacity of reversing valve port A; C_B - liquid capacity of reversing valve port B; R_m - the load of hydraulic motor; I_m - the moment of inertia of load; V_a - hydraulic motor displacement of every rotation; ω - output angular velocity of hydraulic motor; S_e - tank.

Based on bond graph method of state equation is derived, and the independent variable of capacitive element and inertial element integral as state variables,

$V_b = \int Q_b$; $V_A = \int Q_A$; $V_B = \int Q_B$; $V_J = \int Q_J$; $D_J = \int F_J$; $X_1 = \int v_1$; $D_h = \int F_h$; $X_2 = \int v_2$; $X_m = \int T$.

The obtained state equation of system is as follows:

$$\dot{V}_b = Sf - Q_y - \frac{1}{R_b}\frac{V_b}{C_b} - Q_{PA} - Q_X \tag{1}$$

$$\dot{V}_J = Q_X - A_1 \frac{D_J}{I_J} \tag{2}$$

$$\dot{D}_J = A_1 \frac{V_J}{C_J} - \frac{X_J}{C_J} - R_J \frac{D_j}{I_J} - F_S \tag{3}$$

$$\dot{X}_1 = \frac{D_J}{I_J} \tag{4}$$

$$\dot{D}_h = A_2 \frac{V_J}{C_J} - \frac{X_{11}}{C_h} \tag{5}$$

$$\dot{X}_2 = \frac{D_h}{I_h} \tag{6}$$

$$\dot{V}_A = Q_{PA} - V_a \frac{X_m}{I_m} \tag{7}$$

$$\dot{V}_B = V_a \frac{X_m}{I_m} - Q_{BT} \tag{8}$$

$$\dot{X}_m = V_a \frac{V_A}{C_A} - R_m \frac{D_m}{I_m} - V_a \frac{V_B}{C_B} \tag{9}$$

The flow Q_y of relief valve and the port flow Q_{PA}, Q_{BT} of reversing valve are computed as follows:

$$Q_y = \begin{cases} 0, P_b < P_{tiao} \\ \frac{1}{R_y}(P_b - P_{tiao}), P_b \ge P_{tiao} \end{cases} \tag{10}$$

$$Q_x = \begin{cases} 0, X_1 = 0 \\ KX_1(P_1 - P_2)^{1/2}, 0 < X_1 < X_{1m} \\ KX_m(P_1 - P_2)^{1/2}, X_1 \ge X_{1m} \end{cases} \tag{11}$$

$$Q_{PA(BT)} = \begin{cases} 0, X_2 = 0 \\ KX_2 P_{PA(BT)}^{1/2}, 0 < X_2 < X_{2m} \\ KWP_{PA(BT)}^{1/2}, X_2 \ge X_{2m} \end{cases} \tag{12}$$

Where P_{tiao} is overflow pressure of relief valve; P_{PA} is the pressure difference of PA port of reversing valve; P_{BT} is the pressure difference of BT port of reversing valve ; X_{1m} is the displacement when valve port opening of reducing valve is the largest; X_{2m} is the displacement when valve port opening of reversing valve is the largest.

IV. THE SIMULATION AND ANALYSIS ON SYSTEM

A. The establishment of simulation model on system

According to the established power bond graph and the system state equation, the Simulink model of steering system of single axis SPMT is established with MATLAB/Simulink software(as shown in figure 6).

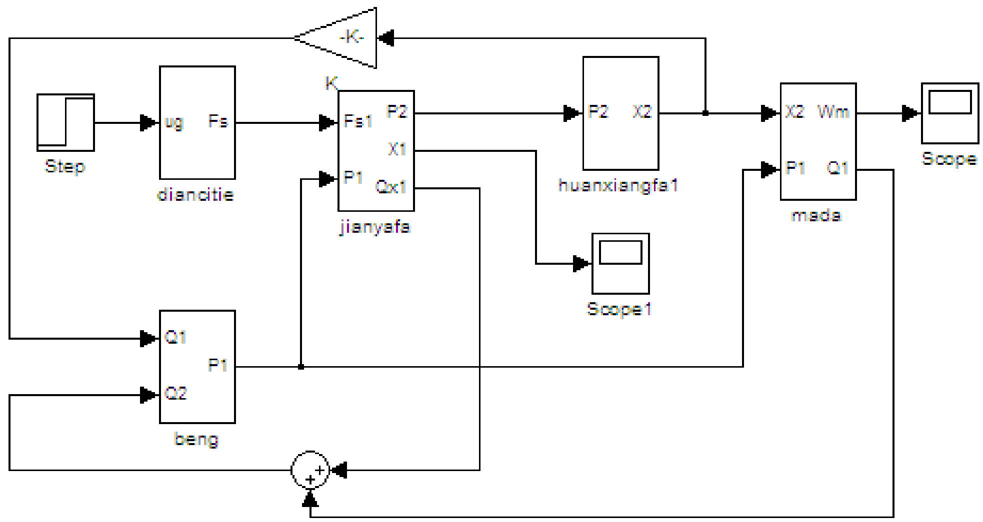


Fig.6 Simulation model of single axle electro-hydraulic proportional steering system

B. The analysis on simulation results

The input signal of proportional electromagnet is voltage which adopts step signal input (solid line) and ramp signal input (dotted line) respectively. The input curves of voltage are shown in figure 7. The variable curve of spool displacement of proportional reducing pressure is shown in figure 8. The outlet pressure curves of proportional reducing pressure valve are shown in figure 9. The variable curve of main spool displacement of reversing valve is shown in figure10. The inlet flow curve of reversing valve is shown in figure 11. The dynamic response curve of output angular velocity of hydraulic motor is shown in figure 12.

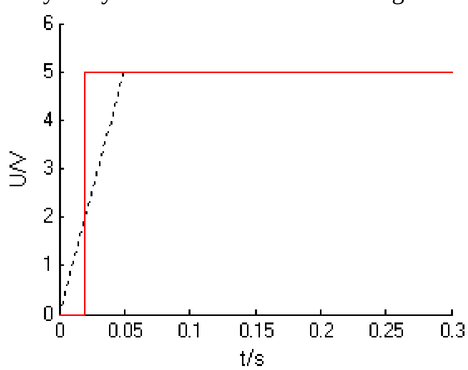


Fig.7 Input the voltage signal

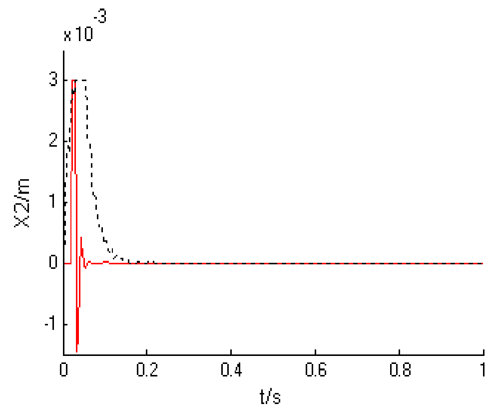


Fig.8 Curve of the proportional relif valve displacement

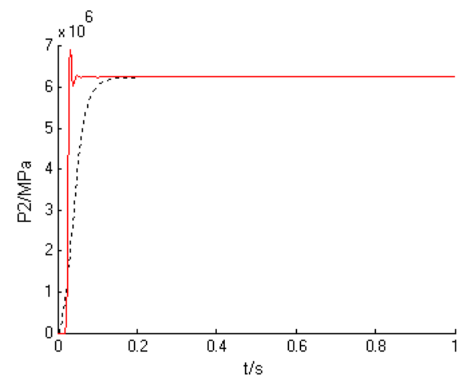


Fig.9 Output pressure curve of proportional relif vale

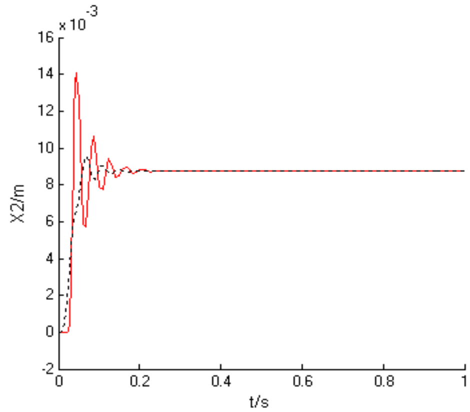


Fig.10 Curve of the change valve spool displacement

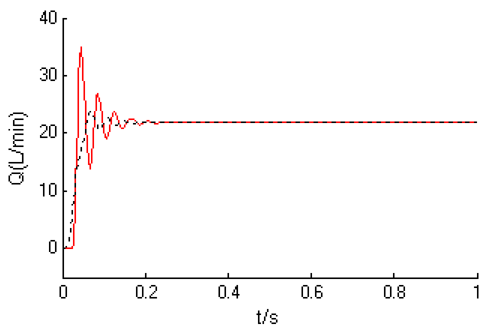


Fig.11 Input flow rate curve

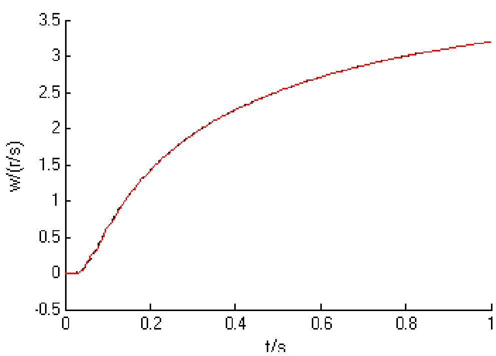


Fig.12 Curve of hydro-motor angular velocity

It can be seen from figure 8 and figure 9 that the spool of pilot valve moves rapidly under the action of electromagnetic force when there is electric current through the electromagnet and the output pressure P_2 acts on spool of reversing valve. The load on spool of reducing pressure valve reaches to balance when the outlet pressure is equal to the electromagnetic force with the increase of P_2. When the system reaches to steady state at t=0.2s, the port of guide reducing pressure valve is closed, so the system has less flow loss and good dynamic characteristics.

From figure 10 and figure 11, It can be seen that the system flow is changed with the change of main spool opening of reversing valve. The system flow has larger fluctuation before the system reaches steady state and voltage of instructions suddenly changes, however the change process is relatively stable.

Figure 11 and Figure 12 shows that the system flow increases with the oil through reversing valve under the action of P_2 on spool of reversing valve. The angular velocity of hydraulic motor increases smoothly and reaches to steady state with force balance of valve spool. Therefore, the system steering is smooth and has good dynamic response features.

V. CONCLUSIONS

The steering system of self-propelled heavy platform car is taken electro-hydraulic proportional reversing valve as the key element which can meet the requirement of vehicle steering pattern such as the straight, oblique line, and spin.

The dynamic characteristics of steering system are analyzed through the MATLAB/Simulink simulation platform. The analysis results show that the system has good stability and good dynamic response.

REFERENCES

[1] Lu Li-qun, Shi Bo-qiang, Guo Peng-yan,etal. Study of Control in Muti-steering Pattern of Self-propelled Heavy Platform Vehicle[J]. Coal Mine Machinery, 2008,29(8)：164-166.

[2] Gao Xiuhua,Zhang Chunqiu,Li Yanling,etal.Steering control modes for multi-wheel steering system[J]. Hoisting and Conveying Machinery, 2006(6)：5-8.

[3] Wu Genmao,Qiu Xiumin,Wang Qingfeng,etal. Electrohydraulic proportional technique in theory and application[M].Hangzhou:Zhejiang University Press, 2006：7-12.

[4] Zhao Jingyi, Wang Zhiyong, Qin Yanming, Wang Jinxiang. Simulation And Experimental Analysis Of Electro-Hydraulic Steering Control System For TLC900 Transporting Girder Vehicle[J]. Chinese Journal of Mechanical Engineering, 2007,43(9)：65-68.

[5] Kou Weiguang,Zhou Huiqun,Yang Jing. Study of Modeling Method for Hydraulic System[J]. Machinery & Electronics, 2010(5)：24-27.

[6] Wang Zhongshuang.Theory of power bond graph and application in system dynamics[M].Harbin:Harbin Engineering Press,2007:8-15.

[7] Paynter H M. Analysis and design of engineering systems[M]. Cambridge: The MIT Press, 1960:132-153.

[8] Karnopp D, Margolis L, System R. Dynamics modeling and simulation of mechatronic systems[M]. New York: John wiley and sons, 2005:232-253.