

## DESIGN AND TEST OF HYDRAULIC DEVICE FOR ELECTRO-HYDRAULIC CONTROLLED HITCH SYSTEM OF A HORTICULTURAL TRACTOR

### 园艺电液控制系统液压装置的设计与试验

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#### ABSTRACT

This paper proposed a structural design scheme of the hydraulic device of the electro-hydraulic controlled hitch system of a YM554A horticultural tractor with hydraulic device model, and the designed hydraulic device was simulated and tested to verify its performance. Results show that the motion of hydraulic actuator is stable with good response for tillage depth control, while the maximum lifting force of 10.62kN and the static settlement value of 13mm all meet the standard requirements. And the oil pressure changes rapidly with a large fluctuation with the plough position changed from transportation state to tillage state, but it quickly stabilizes, and as the tillage depth becomes larger, the oil pressure drops but remains basically stable with the maximum oil pressure change of 0.35MPa.

#### 摘要

本文提出了 YM554A 园艺拖拉机电液悬挂控制系统所用液压装置的结构设计方案,建立了液压装置模型,进行了液压执行器运动仿真和耕作深度控制,测量了系统的提升力和静沉降值,并在田间测量了不同耕作深度下液压执行机构从运输状态到耕作状态的油压。仿真结果表明,液压执行机构的运动是稳定的,对耕作深度控制有良好的响应,特别是在耕作深度变化时,液压执行机构的响应速度快。台架试验结果表明,最大提升力为 10.62kN,半小时内的静沉降值为 13mm,均满足标准要求。田间试验的结果表明,当从运输状态变化到耕作状态时,油压波动大,但是很快稳定下来,而且随着耕作深度变大,油压下降但仍基本稳定,最大油压变化为 0.35MPa。所设计的液压装置静沉降小,起升力大,响应速度快。

#### INTRODUCTION

The hydraulic hitch device of a tractor is an important device to control the agricultural machinery operation, which determines the power performance, operation quality, fuel consumption, exhaust emissions, operation efficiency and so on (Ranjbarian et al, 2017; Eltom et al, 2015). The horticultural tractor based on the traditional tractor platform, which equipped hydraulic controlled hitch system, cannot meet the needs of production and management of modern horticulture operations and facility agriculture in terms of overall structure, energy saving and emission reduction, power transmission and so on. Therefore, modern hydraulic technology, sensing technology, electronic technology and control technology can be adopted to improve efficiency and quality by accurate and rapid adjustment of the hitch system (Wang et al, 2017; Soren et al, 2017; Soren et al, 2018; Suomi et al, 2015; Anthonis et al, 2004).

In 1970s, electronic technology has been applied to farm vehicles to realize the electronic control of tractor's hydraulic hitch mechanism (Lee et al. 1996, and Jiang et al. 1992). Anthonis et al. (2004) established a mathematical model based on the relationship between traction force and three factors such as speed, tillage depth and soil resistance. The dynamic characteristics of the three models were studied respectively, which laid a foundation for the design of the electro-hydraulic controlled hitch system. Later, BOSCH Company and some famous tractor manufacturers such as New Holland and John Deere have already developed their own tillage control system, which makes the technology of electro-hydraulic controlled hitch system more mature. Since the 1990s, some researchers have focused on the research of control algorithm, control system design, core component design of the electro-hydraulic controlled hitch system (Shafaei et al, 2019; Hua et al. 2019; Kang et al, 2015; Chen et al, 2014; Chen et al. 2018; Zhao et al, 2014).

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However, the researches and application of the electro-hydraulic controlled hitch system are mainly aimed at heavy tractors. The researches on electro-hydraulic controlled hitch system are very few for small and middle size tractors, especially for horticultural tractors, and there is a lack of detailed design and in-depth theoretical analysis of the hydraulic devices of electro-hydraulic controlled hitch system.

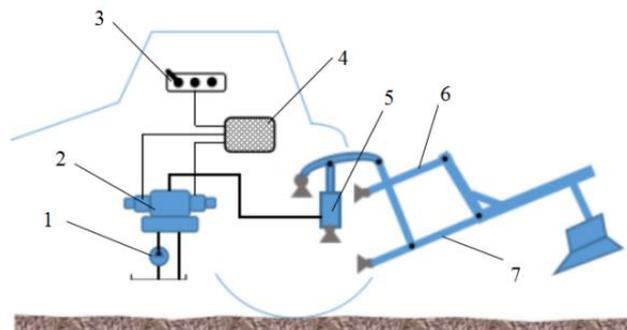
Therefore, the objective of this paper is to aim at horticultural tractor to put forward the design scheme of hydraulic device suitable for electro-hydraulic controlled hitch system, carry out structural design of the hydraulic device and build the hydraulic device model. The designed hydraulic device was simulated and tested to verify its performance.

## MATERIAL AND METHODS

### Design Scheme of Hydraulic Device of Electro-hydraulic Controlled Hitch system

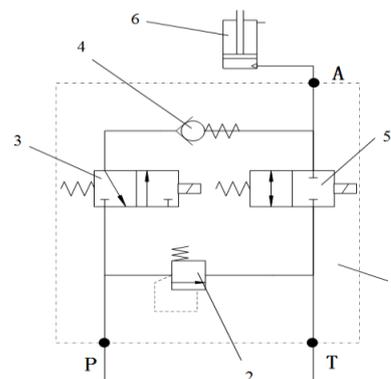
Retaining the raw three-point hitch mechanism, the hydraulic device of an electro-hydraulic controlled hitch system is used to replace the raw mechanical hydraulic device for a YM554Y horticultural tractor. The design requirements are: ① Electrically operated hydraulic valve(s) is (are) used to replace the original distributor. ② Operation panel is used to replace the original control handle. ③ Some sensors for force, displacement or angle measurement are installed. ④ The system has small settlement, sufficient lifting force and rapid response.

The electro-hydraulic controlled hitch system is mainly composed of hydraulic device, hitch mechanism and control system, as shown in Fig. 1. The hydraulic device is electronically controlled by an ECU in the control system, where the electromagnetic proportional valve can change the flow rate and flow direction of the hydraulic oil according to the control signal, so as to drive the hitch mechanism to realize lifting and dropping of farm implements. It is mainly composed of a hydraulic pump, a hydraulic control valve, and a hydraulic actuator. The hydraulic control valve is a combined valve which includes electrically operated 2-position 3-port hydraulic valves, electrically operated 2-position 2-port hydraulic valve, relief valve and check valve in the valve body, as shown in Fig. 2. By combining all kinds of valves above, it can simplify the system structure and reduce the installation space.



**Fig. 1 - Schematic diagram of electro-hydraulic controlled hitch system**

1- Hydraulic pump; 2-Hydraulic control valve; 3-Control panel; 4-ECU;  
5-Hydraulic actuator; 6-Upper pull rod; 7-Lower pull rod



**Fig. 2 - Hydraulic control valve**

1-Valve body; 2-Relief valve; 3-Electrically operated 2-position 3-port hydraulic valve;  
4-Check valve; 5-Electrically operated 2-position 2-port hydraulic valve; 6-Hydraulic actuator

The two electrically operated valves are controlled by the ECU, which can automatically control lifting and dropping of the hydraulic actuator. Here the YM554Y horticultural tractor adopts three-point hitch mechanism, mainly composed of upper pull rod, lower pull rod, lifting rod and so on. The hydraulic actuator provides power to drive the left and right pull rods, thus to control lifting and dropping of farm implements.

The working principle of the hydraulic control valve is that the 2-position 2-port valves and the 2-position 3-port valves are all closed when the ECU does not output the control signal. The oil from the hydraulic pump goes through the port *P* into the valve body, and then flows directly through the relief valve and the port *T* to the oil tank. Meanwhile, because the check valve closes and the 2-position 3-port valve closes, the oil in the hydraulic actuator at the port *A* is cut off, the piston rod of the actuator remains at a certain height, and the farm implements suspended are in a certain position. When the ECU outputs control signal to 2-position 3-port valve, instead of 2-position 2-port valve, the oil passage between the 2-position 3-port valve and the hydraulic actuator is opened, while the oil passage via 2-position 2-port valve is still closed. So, the oil from the hydraulic pump flows into the actuator through the port *P*, the 2-position 3-port valve, the check valve and the port *A*. Therefore, the piston rod extends outwards and the farm implement is lifted.

When the ECU outputs control signal to the 2-position 2-port valve, instead of the 2-position 3-port valve, the oil passage between the 2-position 2-port valve and the actuator is opened, while the oil passage via the 2-position 3-port valve is closed. So, the oil from the hydraulic pump flows back to the oil tank through the port *P*, the relief valve and the port *T*. At the same time, the oil passage between the 2-position 2-port valves and the actuator is opened. Then the oil in the actuator flows back to the oil tank through the 2-position 2-port valves and the port *T*. The piston rod retracts and the farm implement is dropped.

### Design of the Hydraulic Device

Here, the original hydraulic pump remained with the flow rate of 35 L/min, the pump pressure of 20MPa and the pump speed of 2200r/min. But a hydraulic cylinder with single shaft and single flow port is chosen as the hydraulic actuator with the inner diameter of 75mm, the diameter of the piston rod of 35mm and its stroke of 200mm. Then the components of the hydraulic control valve are designed as follows.

The relief valve is a kind of direct-acting threaded cartridge valve (Fig. 3). When the pressure at the RO1 port does not reach 85% of the set pressure of the valve spring, RO1 to RO2 will not pass through. When the pressure at the RO1 port exceeds 85% and continues to rise, RO1 to RO2 will relief until the maximum set pressure of the spring is reached. And the structure of check is shown in Fig. 4. When the pressure of OO1 port is large enough to overcome the spring force, the liquid flow flows from OO1 port to OO2 port with a very low pressure drop, which prevents the liquid flow from OO2 port to OO1 port.

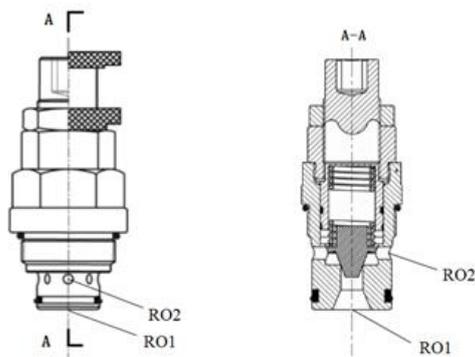


Fig. 3 - Relief valve

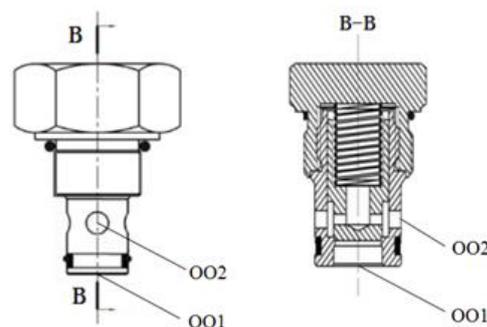


Fig. 4 - Check valve

The electrically operated 2-position 2-port valve is a kind of normally closed threaded cartridge valve powered with a 12 V DC voltage (Fig. 5). When it is not electrified, the oil passage will be closed between VO1 port and the VO2 port; otherwise the oil passage will be opened between the VO1 port and the VO2 port. And the electrically operated 2-position 2-port valves is a sliding valve powered with a 12 V DC voltage (Fig. 6), which controls the flow direction by changing the position of the inlet and outlet passage of the fluid. When it is not electrified, the oil passage between the VO2 port and the VO3 port is closed, while the oil passage between the VO2 port and the VO1 port is opened. When it is electrified, the oil passage between the VO2 port and the VO3 port is opened, while the oil passage between the VO2 port and the VO1 port is closed.

**Model of Electro-hydraulic Controlled Hitch system**

**Model of Hydraulic Components**

According to the design scheme above and the design of the main hydraulic components, the hydraulic components were modelled by using AMESim software, as shown in Fig. 7, where the mass block was used to replace the farm implement, the resistance force block provided the tillage resistance force, the displacement sensor outputs the displacement signal of the hydraulic actuator, the pressure sensor outputs the oil pressure signal, and the sensor signals above were input into the interface icon Simulink control. Then one of its outputs loaded to the mass block by converting the resistance force of the actuator into the tillage resistance force via a gain, and the other output were current signals, which controlled the action of the two electrically operated valves.

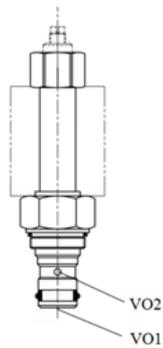


Fig. 5 - Electrically operated 2-position 2-port valves

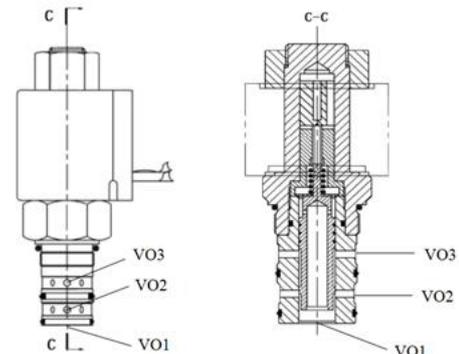


Fig. 6 - Electrically operated 2-position 3-port valve

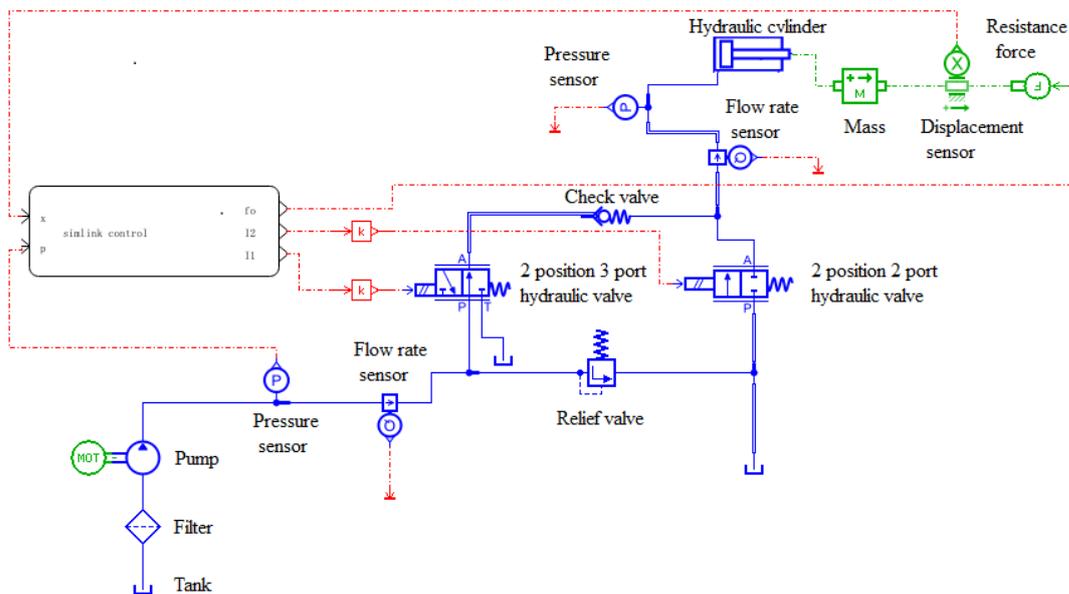


Fig. 7- Model of hydraulic components

**Model Parameters**

Taking a plough implement as an example, its weight is 200kg and the width of single plough is 30cm. The tillage depth is set to 20cm, while the specific resistance of soil is 5N/cm<sup>2</sup>. The equivalent mass *M* of the load acting on the piston is expressed as:

$$M = k \cdot m \cdot i_g^2 \tag{1}$$

In the formula, *k* is the correction coefficient, it is set to 1.05 here; *m* is the mass of farm tool, it is set to 200 kg here; *i<sub>g</sub>* is the lifting speed ratio at the centre of gravity of the farm implements, and the lifting speed ratio is 6.

According to the above formula, the equivalent mass *M* can be calculated to be 7560 kg. The model parameters are shown in Table 1.

Table 1

Parameters of the model		
Name	Number	Unit
Flow rate of hydraulic pump	35	L/min
Hydraulic pump pressure	18	MPa
Hydraulic actuator diameter	75	mm
Hydraulic actuator rod diameter	35	mm
Piston stroke	200	mm
Voltage of electrically operated valve	12	V
Oil pressure of Electrically operated valve	20	MPa
Gain	6	
Mass of mass block	7560	kg

**Model of Control System**

An interface icon S-Function in Matlab Simulink was used to import the build AMESim model of the hydraulic components, while a PID controller was established to verify performances of the designed hydraulic device. The established model of the control system is shown in Fig. 8.

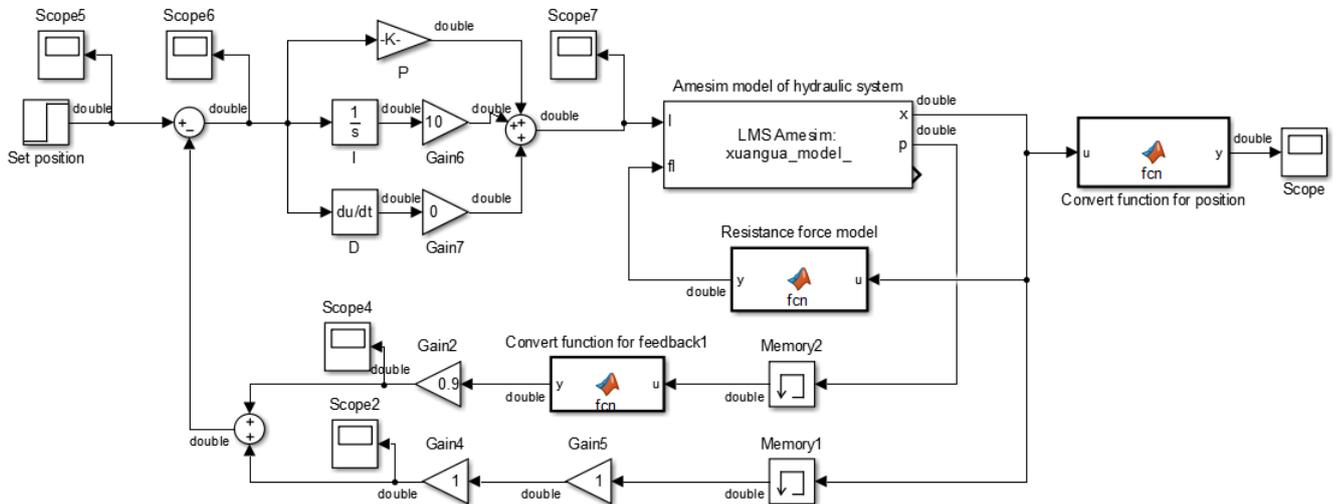


Fig. 8 - Model of control system

**RESULTS**

**Simulation of Hydraulic Actuator Motion**

The initial piston displacement is set to 0, and the preset piston displacement is set to 0.2 m to observe the piston movement (Fig. 9 and Fig. 10) and the flow of piston orifice (Fig. 11).

From Fig. 9 and Fig. 10, it takes piston displacement about 6.3 s from 0 to 0.2 m. At the same time, the piston's beginning speed reaches the maximum at 0.186 m/s, then its speed gradually decreases, and the piston moves smoothly after about 1.8 s.

From Fig. 11, the piston flow rate increases at first and then tends to stabilize after about 1.8s. Therefore, it shows that the hydraulic device has good stability through the piston displacement, velocity and flow chart.

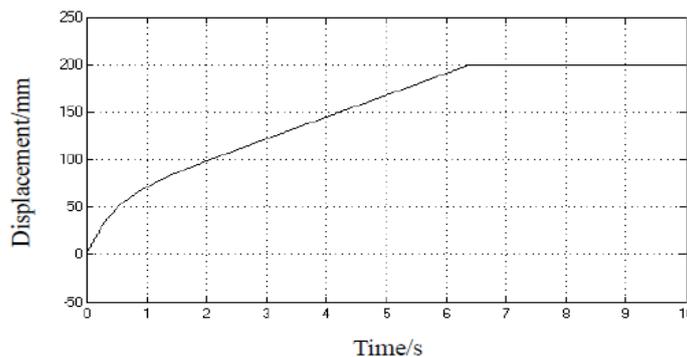


Fig. 9 - Displacement of piston in hydraulic actuator

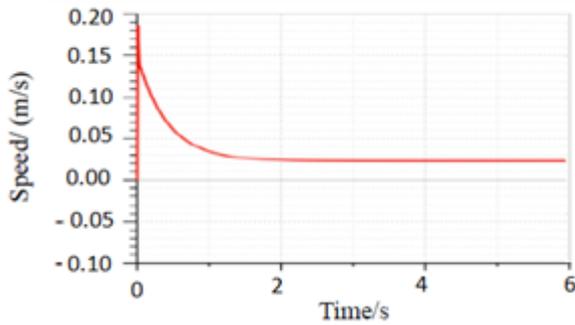


Fig. 10 - Motion speed of piston

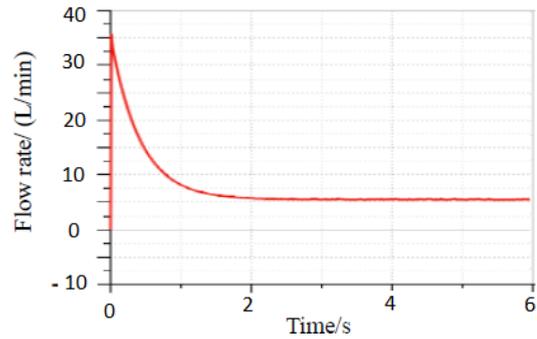


Fig. 11 - Flow rate of piston port

**Simulation of Tillage Depth Control**

The simulation of tillage depth control is to test the responsiveness of the model when the tillage depth changes according to Fig. 8. Firstly, the target value of tillage depth is set to 30cm with the simulation time of 6s. The simulation result (Fig.12) shows that the set tillage depth can be achieved after about 1.8s, and the lifting curve is very smooth with no significant oscillation.

Then the responsiveness of the system is verified. The set tillage depth is changed to 48 cm at a certain time after reaching the set tillage depth of 30 cm. The response result of the change of the set tillage depth is shown in Fig. 13.

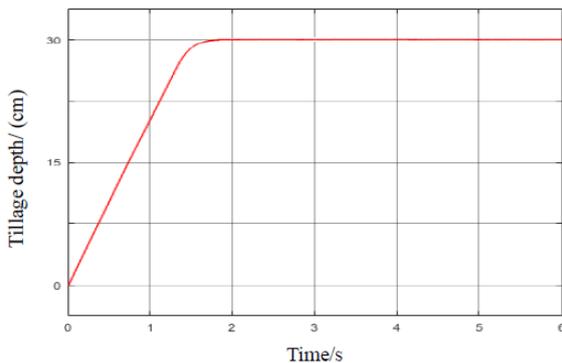


Fig. 12 - Curve of tillage depth

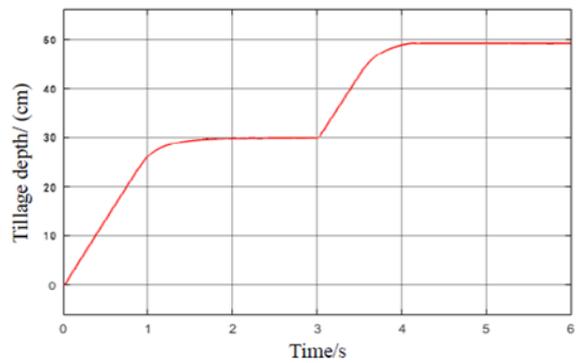


Fig. 13 - Curve at the change of tillage depth

It shows that it takes about 1.8s to reach the set tillage depth of 30cm with no significant oscillation. Then it takes about 3s to convert to the tillage depth of 48 cm, and it reaches the set tillage depth of 48cm after 1s. It shows that the system has good transient response characteristics.

**Test Bench Experiments**

The designed hydraulic control valve (Fig. 14 (a)) was installed on the tractor electro-hydraulic control test bench (Fig. 14 (b)). According to the test standard in China (GB/T 3871.4-2006, 2006), the lifting force and static settlement value were tested at the loading point of the lifting frame mounted on the three-point linkages with the specified pressure value of 16MPa±0.5MPa (see Fig. 14 (b)). The experimental results are shown in Table 2.



(a) Hydraulic control valves



(b) Tractor electro-hydraulic control test bench

Fig. 14 - Test of hydraulic control valve

According to the data in Table 2, the maximum lifting force of the hydraulic hitch mechanism is 10.62kN, which is calculated according to the calculation equation of the maximum lifting force in the test standard (GB/T 3871.4-2006, 2006), and the total static settlement value is 13mm in half an hour, which are in accordance with the standard requirements. Therefore, the designed hydraulic device meets the requirements through the test bench experiments.

Table 2

Test location number	Lifting force test		Static settlement test
	Lifting force at loading point (kN)	Relief valve opening pressure (MPa)	Height(mm)
Test location 1	16.04	16.5	823
Test location 2	15.42	16.3	820
Test location 3	14.69	16.3	819
Test location 4	13.86	16.3	816
Test location 5	13.07	16.2	812
Test location 6	12.33	16.2	810

### Field Experiments

To further verify the performance of the designed hydraulic control valve, it was installed on a YM554 tractor with a XL-425 plough. An oil pressure sensor was installed in the oil tube connected to the hydraulic actuator. The oil pressure was measured during the period from transport state to the tillage state with different tillage depth of 80mm, 120mm and 180mm, respectively. During the whole process, the tractor speed is basically stable at 1 km/h. The variation of the oil pressure and the tractor speed are recorded in Fig. 15.

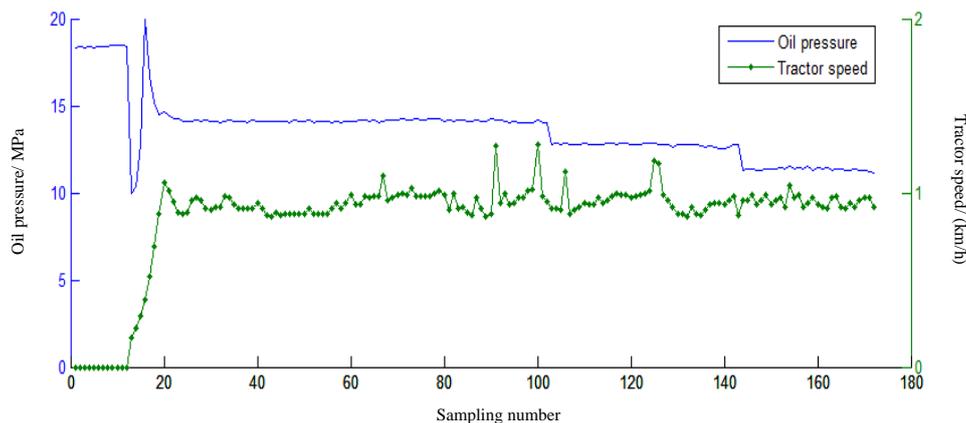


Fig. 15 - The change of the oil pressure in hydraulic actuator and tractor speed

From Fig.15, the tractor speed is basically stable at about 1km/h with the maximum speed of 1.28km/h and the minimum speed of 0.88km/h in the process of tractor farming. As to the oil pressure, it is larger at the transportation state and drops rapidly when the plow changes from the transportation state to the tillage state, then it fluctuates to a certain extent and it stabilizes quickly to 14.1MPa with small fluctuation of 0.31MPa after the tillage depth reaches 80 mm. With the increase of tillage depth, the oil pressure drops, but it keeps stable basically to 12.7MPa and 11.3MPa with small fluctuation of 0.28MPa and 0.35MPa at the tillage depth of 120mm and 180mm respectively. Therefore, the designed control valve has quick response to adapt the changes from transportation state to tillage state with large fluctuation of oil pressure and changes of tillage depth without significant fluctuation and the oil pressure remain basically stable at a certain tillage depth.

### CONCLUSIONS

Aiming at YM554Y tractor, this paper puts forward the structural design scheme of the hydraulic device of the electro-hydraulic controlled hitch system, carries out the structural design of the hydraulic device, then builds the hydraulic device model based on AMESI and Simulink software, and finally carries out the simulation of hydraulic actuator motion and the simulation of tillage depth control and the test bench test.

The results of hydraulic actuator motion simulation and tillage depth control simulation show that the hydraulic actuator motion is stable and the response of tillage depth control is good, especially when the tillage depth changes, the hydraulic device can respond quickly.

The lifting force and static settlement test of the system on the test bench show that the hydraulic device designed meets the requirements. And the designed control valve has quick response to adapt the changes of operating states of the farm implement according to the field experiments, with basically stable oil pressure at a certain tillage depth. This study can provide reference for the development of electro-hydraulic controlled hitch system of tractors.

## ACKNOWLEDGEMENT

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