Design and Experiment of Electronic-hydraulic Loading Test-bed Based on Tractor's Hydraulic Steering By-wire

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Abstract An Electro-hydraulic loading system is designed based on a test-bed of tractor's hydraulic steering by-wire. To simulate the steering resistance driving tractor in many kinds of soils and roads, the loading force is controlled to make proportional and continuous variable by an electro-hydraulic proportional relief valve. A steering resistance loading test-bed is built to test three kinds of steering resistance including constant, step and sine style. Tire lateral resistance is also tested under different steering conditions. The result shows that the electro-hydraulic loading system has high stability and following performance. Besides, the system's steady state error is lower than 3.1%, and it meets the test requirement of tractor's hydraulic steering by-wire.

Key words Tractor, Hydraulic steering by-wire, Loading system, Electro-hydraulic proportional relief valve, Bench test

1 Introduction

With the electronic control technology applied on tractor more and more widely, the electro-hydraulic steering-by-wire system (EHSWS) will be applied on tractor in the near future. The EHSWS has larged force and stronger rigidity than hydraulic steering system [1]. Compared with hydraulic power steering system, it is divided into the steering wheel subsystem and wheel steering control subsystem, and the two subsystems are connected with CAN bus[2]. The pros and cons of steering performance are extremely important to handling stability, driving safety and the working efficiency of vehicle [3]. During steering, the steering resistance influences steering system, especially the road feeling part [4–5]. As the performance test part for development and design of steering system, loading system needs to simulate different steering resistance based on the actual situation of tractor, which is the important basis of the study on road feeling control. At present, the tractor steering operation condition is poor and complex, and the development of tractor's steering test-bed is immature. In addition, there are a lot of shortcomings in testing methods and means [6-7]. Hence, a loading steering test-bed based on the tractor's hydraulic steering-by-wire system has been designed and developed, and related steering loading test has been carried out.

2 Steering resistance torque calculation of tractor

The analysis and calculation of tractor's steering resistance torque can be divided into hard ground and soft ground. When the tractor steers on the hard ground, the generation of the steering resistance torque is due to the deformation between tire and soil where tire needs to overcome the side force from the ground [8–9]. When the tractor steers on the soft ground, the steering resistance also includes the force where tire destroys soil structure with the sinking of the wheel [10]. Tractor's resistance torque turning fixedly is more than driving about 2 to 3 times. Therefore, using steering resistance torque turning fixedly which is an important parameter of design and development loading system can make the tractor steering steady under adverse conditions [11].

2.1 Steering resistance torque calculation on the hard terra

As an example for agricultural four wheel drive (4WD) tractor of model JS-754 made in China, the steering resistance torque of 4WD tractor turning fixedly on asphalt pavement is calculated. According to the empirical formula [12]:

$$M_{R1} = \frac{1}{\eta} G_1 \xi \sqrt{e^2 + r^2} \quad (1)$$

where M_{Rl} is the friction steering resistance torque; η is the transmission efficiency of the steering system; G_1 is the vertical load in the front axle; ξ is the comprehensive friction coefficient; e is the intersection point distance between the terra contact points of tire center and the steering knuckle; r is the equivalent radius, $r = b/3$; b is the width of tire.

The transmission efficiency of tractor electro-hydraulic steering system is low, η picks up 0.85. The weight for 4WD tractor front axle is 1420kg, so $G_1 = \mathrm{m} \cdot \mathrm{g} = 13916$N (g picks up 9.8N/kg). As an example for asphalt pavement, ξ takes 0.8. In addition, e takes 91mm in the 4WD tractor and tire width b is 233.68mm. By the calculation, maximum steering resistance torque M_{R1} turning fixedly on asphalt pavement is 1568.87 Nom.

2.2 Steering resistance torque calculation on the soft terra

Based on the mohr-coulomb theorem, the shear strength q_u of soil is as follows:

$$q_u = 2C \tan(45° + \frac{\phi}{2} \quad (2)$$

where C is the cohesion of soil; ϕ is the internal friction angle of soil.

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When the tractor turns fixedly in dry soil, the cohesion C of soil takes 30kPa, the internal friction angle ϕ of soil is 15°. By the calculation, the shear strength of soil is 78.2kPa. The following formula can be used to calculate the torque destroying soil structure by tire when the tractor turns fixedly.

$$M_{R2} = q_u AL \cos\theta \tag{3}$$

where M_{R2} is the shear steering resistance torque; A is the tire contact area of shear soil; L is the wheelbase; θ is the wheel rotation.

The tire contact area of shear soil for model JS-754 tractor is $1.65 \times 10^{-3} m^2$, wheelbase is 2115mm, and maximum wheel rotation is 45°. By the calculation, $M_{R2} = 192.95N \cdot m$. Therefore, when the tractor turns fixedly in the field, the maximum steering resistance torque $M_{\mu c}$ is as follows:

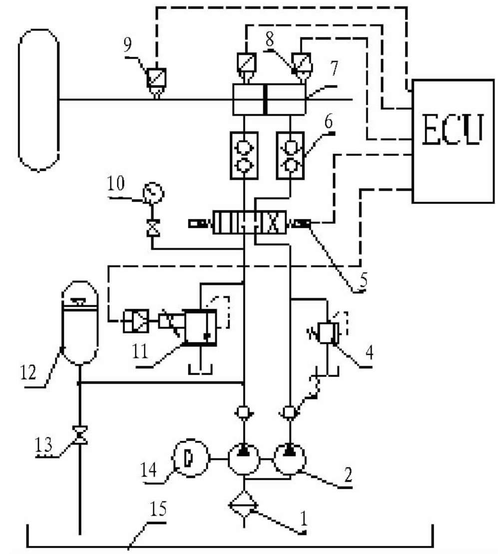
$$M_{\mu c} = M_{R1} + M_{R2} = 1568.87 + 192.95 = 1761.82N \cdot m.$$

3 Loading system design of tractor electro-hydraulic loading test-bed

The loading test-bed of EHSWS consists of a hydraulic unit and a controlling unit.

3.1 Hydraulic unit The hydraulic unit of the EHSWS loading test-bed will load the steering resistance, and is composed of a double gear pump, a proportional directional valve, a loading cylinder, a proportional relief valve, AC motor and so on. The hydraulic unit is shown in Fig. 1. The structural characteristics of single hydraulic cylinder and steering trapezoidal lead on hydraulic steering-by-wire system can be advantageous, so the symmetrical arrangement of loading cylinder is selected. The function of resistance load simulation is achieved by the piston rod of loading cylinder output force on the steering knuckle. The electro-hydraulic proportional relief valve is used to control the pressure in main lines to realize the control of loading force. And the electromagnetic reversing valve is used to choose the work in terms of the tractor actual working condition to realize the selection of loading force direction. The relief valve placed in the auxiliary lines has an effect on back pressure balance which avoids the static work dead zone of the electro-hydraulic proportional relief valve when the pressure is small. The double gear pump supplies oil for main and auxiliary lines at the same time which reduces the pressure fluctuations of output caused by flow changes for the electro-hydraulic proportional relief valve and relief valve, and ensures the system dynamic balance of output pressure to realize the accurate simulation of steering resistance by using hydraulic cylinder piston rod.

3.2 Control system design Electronic control unit (ECU) of the loading system is the core of main system controller. In addition, the main system controller includes some external circuits, such as the drive circuit of electro-hydraulic proportional relief valve and electromagnetic reversing valve, the signal acquisition circuit of sensor, etc. The system control block diagram is shown in Fig. 2. The system control process is as follows. Initially, the electromagnetic reversing valve is controlled by ECU to choose the corresponding work in regard to the signals of loading cylinder dis-



1-oil filter; 2-double gear pump; 3-check valve; 4-relief valve; 5-electromagnetic reversing valve; 6-hydraulic connector; 7-loading hydraulic cylinder; 8-oil pressure sensor; 9-displacement sensor; 10-pressure gage and switch; 11-Electro-hydraulic proportional relief valve and amplifier; 12-accumulator; 13-high pressure valves; 14-AC motor; 15-oil tank.

Fig. 1 Schematic of loading system

placement sensor which is used to realize the selection of loading force direction. Meanwhile, PID control can be adopted by comparing the target loading force signal from the signal generator with the feedback signals from the main oil pressure sensor to control the voltage of electro-hydraulic proportional relief valve which can control the electro-hydraulic proportional relief valve to produce the relief pressure required by the system [13], and make the system to export the steering resistance accurately. The control principle of loading system is shown in Fig. 3.

4 Test and analysis

4.1 Test method Based on the tractor driving condition on offroad, three steering resistances, that is constant, step and sine style, are simulated on the loading test-bed of the tractor's hydraulic steering by-wire. The three parameters of PID should be adjusted online in regard to the oil pressure feedback signals of the oil pressure sensor installed in the steering cylinder at the same time, which achieves fast, stable and accurate loading simulation. The data acquisition card (USB 4716 model) is used to collect the signals from a signal generator, an oil pressure sensor of steering cylinder and a position sensor of the steering cylinder. In addition to this, designing interface by using Labview software is realized to display the change curve of signal and store data in real time, which is easy to analyze the further test results.

4.2 Test design Based on the condition of tractor steering under actual driving condition, three kinds of loading signal mode can be inputted, that is constant signals, step signals and sine signals [14]. The output of constant loading resistance is mainly used to simulate steering resistance that tractor steers fixedly and low-

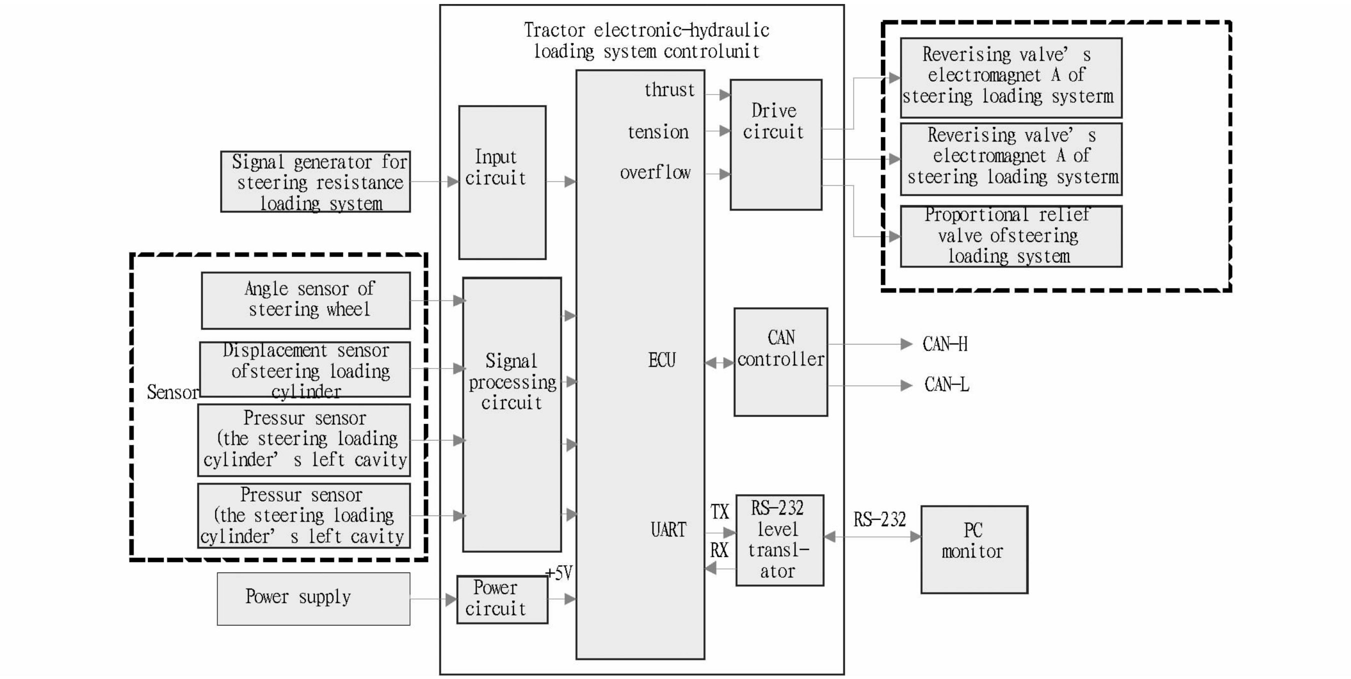


Fig. 2 The controlling layout of loading system

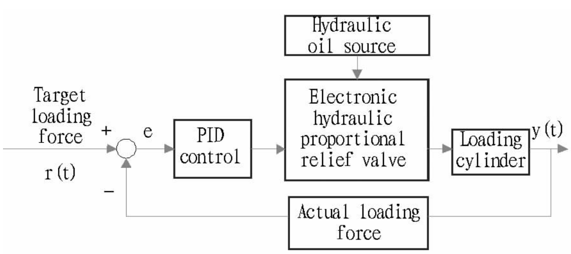


Fig. 3 Schematic of controlling

speed driving with a fixed angle. The value of steering resistance is influenced by road condition, velocity and wheel rotation speed, etc. The output of step loading resistance is used to simulate the steering conditions of the driving direction of the wheel changing suddenly to avoid obstacles in the field or road. The output of sine loading resistance is mainly used to simulate the lateral resistance force when the tractor steers on washboard roads [15]. In addition, the driver turns the steering wheel uniformly and continuously when the tractor goes in a snake-like route. The lateral force of tractor is also changed in accordance with sine law at this moment.

4.3 Experimental results and analysis The closed-loop PID control method is adopted by the steering loading control system in terms of the input loading signal and actual steering resistance signal is measured by cylinder pressure sensor to realize the oil pressure closed-loop control through the electro-hydraulic proportional relief valve. The loading force curves under three kinds of input loading signals are shown respectively in Fig. 4. Cylinder pressure is set at 3MPa, that is to say, the steering resistance simulated by loading system is set at 5.1 kN. The signal input is adopted in a constant way, and the curve is represented for the shift of the simulated steering resistance and time. Fig. 4 (a) shows that when the steering resistance simulated constantly by loading system is set at 5.1kN, the maximum rise time of loading system is 0.55s, the maximum error is 3.1% and the average error is 2.3%. That meets the design requirements of loading system. In addition, when the oil pressure is too low, the loading system will produce small oscillation. This reason is the dead zone of the proportional relief valve. In a word, the loading system is blessed with the ability of high stability and following performance and meets the test requirements of hydraulic steering by-wire test-bed basically. Fig. 4 (b) shows that the response time of the loading system is within 1.1s when the input signal is step signal. The system has a steady-state error and the average steady-state error of system is 1.2%, so the system is blessed with the ability of high stability. The Fig. 4 (c) shows that the change of input sinusoidal signal is followed by the loading system. The system will be oscillated when the loading force lies in the trough of the sine wave due to the low oil pressure. So the overall trend of loading force is that the wave crest is better than the wave trough. The maximum track delay time of sine wave is 0.73s, and the system has the ability of high following performance. Therefore, the actual loading force is better following the target loading force for change. The results of test show that the loading system meets the requirement of development, design and performance test basically in hydraulic steering-by-wire system. In addition, the corresponding test resistance can be provided according to the performance testing requirements of steering system to simulate the resistance where different kinds of road act on the steering system, and achieve a valid test for the vehicle steering system. In the process of loading test, the gaps must exist between the actual loading force and the target loading force due to the damping force of hydraulic oil, the resistance between pipe and joint in the oil connection, hydraulic oil leaks, vibration and noise, etc.

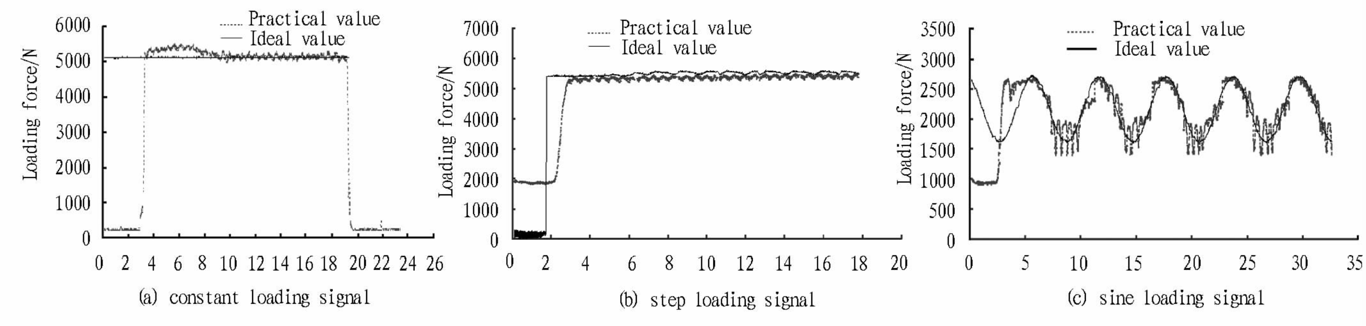


Fig. 4 Loading force response curve

5 Conclusions

(i) As an example for 4WD tractor of model JS-754, the maximum steering resistance torque in the process of steering has been analyzed and calculated under the conditions of hard ground and soft ground. The torque is 1568.87 Nom and 1761.82 Nom, respectively. (ii) The loading system of hydraulic steering-by-wire test-bed has been adopted by the method of electro-hydraulic loading. In addition, the electro-hydraulic loading test bench has been set for the loading simulation experiment of steering resistance. (iii) In the loading test bench, the resistance loading simulation experiment has been carried out. And the input signal of loading control system includes constant signal, step signal and sine signal which can be used to simulate tire lateral resistance when tractor steers under different working conditions. (iv) The maximum error of signal tracking is 3.1%, the average error is 2.3%, the maximum delay time is 1.1s. Hence, the electro-hydraulic loading system has the ability of high stability and following performance.

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