RESEARCH ON THE STEERING CHARACTERISTICS OF ELECTRO-HYDRAULIC COUPLED STEERING SYSTEM OF SELF-DRIVING TRACTOR
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自动驾驶拖拉机电液耦合转向特性研究

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DOI: https://doi.org/10.35633/inmateh-73-51

Keywords: *self-driving tractor, E-HCSS, steering characteristics, multifactorial experiment*

ABSTRACT

To solve the problem of poor steering performance of existing self-driving tractors based on electro-hydraulic coupled steering systems (E-HCSS) under multiple influencing factors, the research on electro-hydraulic coupled steering characteristics of self-driving tractors was carried out in this paper. Taking the electro-hydraulic coupled steering system as the research object, the E-HCSS test bench of the tractor was built, and the influencing factors affecting the responsiveness of the steering process were obtained through theoretical analysis: hydraulic fluid temperature, oil supply pressure and driving speed. The hydraulic fluid temperature, oil supply pressure and driving speed were taken as the test factors, and the steering system response time and response error were taken as the performance indexes for the single-factor steering test and orthogonal test. By establishing the regression mathematical model between the influencing factors and the indexes, the interactive influence of the factors on the indexes was analyzed, the optimal parameter combination was obtained, and the optimization results were verified. The test results indicated that the tractor electro-hydraulic coupling steering system could achieve good steering performance under the optimal parameter combination, and the optimal parameter combination was: hydraulic oil temperature 60°C, hydraulic oil pressure 15 MPa and driving speed 8 km/h. The study's results were as follows: hydraulic oil temperature 60°C, hydraulic oil pressure 15 MPa and driving speed 8 km/h. The study's results could provide a reference for the steering control of the self-driving tractor, the design of the self-driving steering system and the optimization of the parameters.

摘要

为了解决现有基于电液耦合转向系统的自动驾驶拖拉机受多重影响因素下的转向性能差的问题，本文进行了自动驾驶拖拉机电液耦合转向特性研究。以电液耦合转向系统为研究对象，搭建了拖拉机电液耦合转向试验台，通过理论分析得到了影响转向过程响应能力的影响因素：液压油油液温度、供油压力及行驶速度。以油液温度、供油压力及行驶速度为试验因素，以转向系统响应时间、响应误差为性能指标进行转向单因素试验及正交试验。通过建立各影响因素与指标之间的回归数学模型，分析各因素对指标的交互影响，获得最优参数组合，对优化结果进行验证试验，试验结果表明在最优参数组合下拖拉机电液耦合转向系统能够达到良好的转向性能，最优参数组合为：液压供油温度60°C、液压供油压力15MPa及行驶速度8km/h。研究结果可为自动驾驶拖拉机转向控制、自动驾驶转向系统设计及参数优化提供参考。

INTRODUCTION

Self-driving tractors are important technological means for the implementation of precision work and the development of modern agriculture. However, the influence of different factors on the steering performance of self-driving tractor is not clear which makes the self-driving control challenging (*Fang S. et al., 2017*).

There are two main existing structural steering systems for self-driving tractors. One is modified on the basis of the original tractor hydraulic power assist system, and a solenoid valve is connected in parallel. The steering control is carried out by controlling the opening of the solenoid valve (*Lee C., 2022; Zardin B., 2018*). Another is not to change the original hydraulic steering system, and the steering motor and the corresponding deceleration structure are added in the steering column or steering wheel.

Steering is realized by controlling the rotation of the motor and then driving the steering column and the hydraulic steering part (*Xu G. et al., 2020*). Because the parallel solenoid valve needs to change the original oil circuit, the modification cost is higher, the implementation is difficult, so the second program is applied more often. However, the second program has two power sources—electric and hydraulic, so its steering performance is susceptible to the influence of various parameters within the steering system and other factors (*Kralev J. et al., 2019*). Especially in the process of operation, multiple factors can seriously affect the steering performance of the self-driving tractor, which in turn affects the operation results (*Lindhorst C., 2019*).

Due to the unclear steering characteristics of electro-hydraulic coupled steering system (E-HCSS), the corresponding controller was designed to attenuate the multiple influences on the steering system as uncertainties and parameter perturbations to ensure the control of the tractor (*Liu Y. et al., 2020*). *(Xu G. et al., 2021)* proposed a path tracking control method based on E-HCSS considering external disturbances and uncertainties. *(Zhao W. et al., 2019)* considered the energy loss and optimized the parameters of the E-HCSS. Due to the complex structure of the hydraulic system, the wide range of steering loads and the difficulty of control, *(Du H. et al., 2020),* proposed an improved integral sliding mode control method to improve the steering control accuracy.

However, since the E-HCSS is a composite system involving mechanical, hydraulic, and electrical components, its system characteristics are subject to multidimensional changes due to multiple factors such as oil temperature, oil pressure, and driving speed (*Tang B. et al., 2015*). Simplifying the influences on the steering system to uncertainties and parameters makes it difficult to ensure steering performance under tractor-specific characteristic factors. Therefore, it is necessary to explore the influencing factors of E-HCSS to clarify its steering characteristics and intrinsic steering coupling mechanism, so as to improve the steering performance (*Feng J. et al., 2023*).

The motivation of this work is to find the optimal combination of performance parameters of E-HCSS. The working performance of E-HCSS always suffers from multiple factors including oil temperature, oil pressure, and driving speed, et.al. To achieve better response time and response error of E-HCSS integrate in self-driving tractor, single factor test and orthogonal test with E-HCSS under steering condition are carried out and the optimal parameter combination is obtained which is not hitherto reported in the open literature. One of the advantages and contributions of the research is that it provides a way to find a relationship between self-driving performance and multiple parameters of E-HCSS—oil temperature, oil pressure and driving parameter—driving speed etc.

MATERIALS AND METHODS

Whole structure of E-HCSS

In order to carry out research on tractor E-HCSS characteristics and simulate the steering scenarios of tractors under actual working conditions, a tractor E-HCSS hardware-in-the-loop (HIL) test bench was constructed by using the hydraulic power steering system of the tractor as the substructure, and coupling the hydraulic pressure with the power assisting motor in the steering shaft (*Xu G et al., 2020*). Fig. 1 shows the structure of the E-HCSS which mainly consists of steering module, hydraulic power module, power supply module, resistance loading module, human-machine interaction module, support module and so on.

Steering module mainly consists of full hydraulic steering system and motor steering system. The two are connected by a pipe column, which is mounted on a circular column support at an angle of the real vehicle, and the circular ball steering device is connected by a universal joint. The hydraulic power and an electric motor torque acting together to execute the steering signals from the controller of the self-driving tractor, and the hydraulic pressure provides a large steering power at low speeds, which reduces the loss of energy consumption.

Hydraulic power module mainly consists of 15 kW three-phase asynchronous motor, hydraulic pump, oil temperature controller, hydraulic pressure controller. The module is used to provide a hydraulic source with a maximum supply pressure of 20 MPa and a maximum flow rate of 14 L/min. The oil temperature controller can regulate the oil temperature and the hydraulic pressure controller can regulate the oil supply pressure. In order to improve the reliability of the hydraulic system, the pump station has a hydraulic oil filtering function.

The power supply module mainly provides the appropriate voltage for the various power modules of the test stand to keep the whole bench working properly.

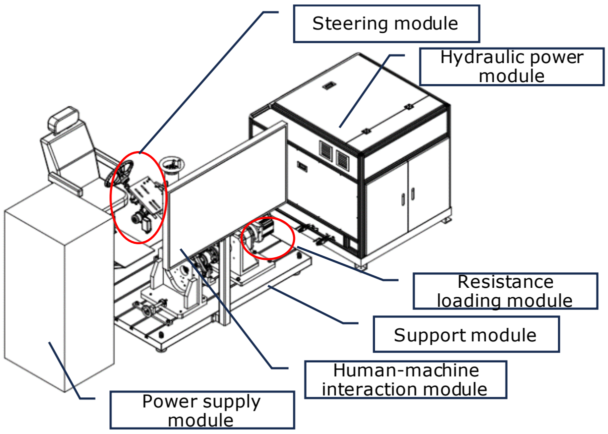


Fig. 1 - Structure drawing of tractor E-HCSS

The resistance loading module is mainly composed of servo motor, reducer, coupling assembly, pull pressure sensor, etc. It is mainly used to simulate the steering resistance loading provided for the electro-hydraulic coupled steering module to satisfy the real dynamics relationship, so as to make it closer to the real operation environment.

The human-computer interaction module mainly consists of a monitor, a seat, a steering wheel and so on. The monitor is used to display the running screen of the tractor model in the set operating environment in real time. It can provide an interface for human-computer interaction, and can be used for driving simulation.

The support module adopts cast iron platform structure, which is mainly composed of base and circular column module. Among them, the circular column module is mainly composed of screw, rotary table, handwheel, sliding block and so on. It is used in combination with the column fixture to realize the installation of different columns at different heights and angles.

Working principle of E-HCSS

The working principle of the E-HCSS is schematically shown in Fig. 2. Based on the original fully hydraulic steering system of the tractor, the steering motor is connected in series. The self-driving controller controls the rotation of the steering rod by controlling a motor connected in series to the upper end of the vehicle. Turning of the steering rod opens the rotary valve. The oil flowing through the rotary valve is fed into the hydraulic cylinder to generate hydraulic power. The power of the motor and the power of the hydraulic pressure work together to produce a steering force to overcome the steering resistance and the friction within the steering system.

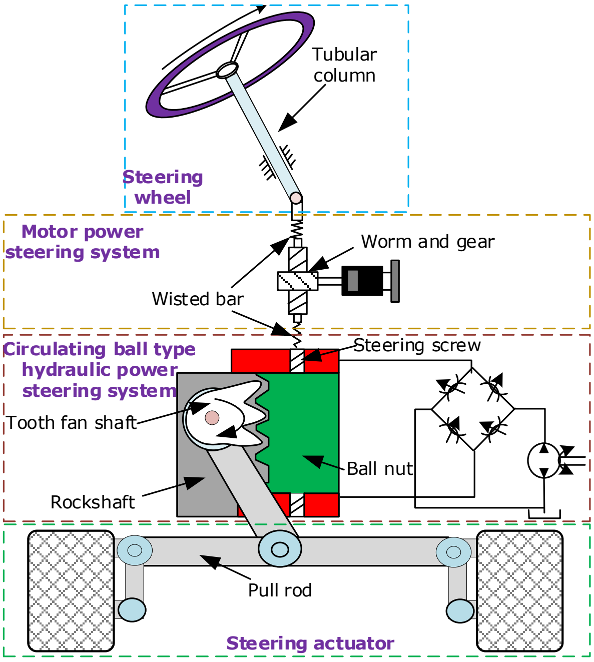


Fig. 2 - Schematic diagram of E-HCSS

Analysis of factors affecting steering system performance

The steering motor output torque T_a of the E-HCSS and the hydraulic power F_L of the hydraulic steering system work in concert to overcome the steering resistance T_r and the internal friction T_f so that the tractor can execute the steering command. The steering dynamics are modeled referring to (*Shi G et al., 2023*).

Under the joint action of motor power and hydraulic power, the control principle block diagram is shown in Fig. 3.

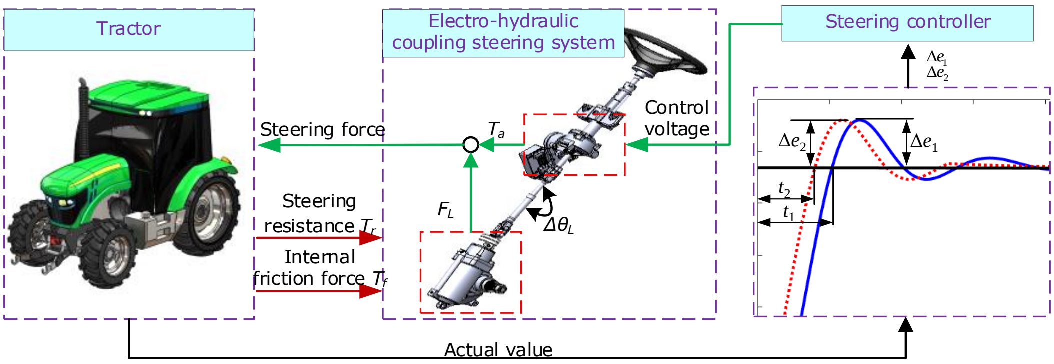


Fig. 3 - Control principle diagram of E-HCSS

It can be known from the dynamics relationship and Fig. 3 that hydraulic power F_L affects the dynamics relationship of the steering system. F_L will be affected by the oil supply pressure, oil temperature and other factors, which in turn affects the response time of the control system, $t_{1, 2...}$ and the response error, $\Delta e_{1, 2..}$, and steering resistance likewise affects the dynamics of the steering system relationships (*He X et al., 2022*). Furthermore, the steering resistance is related to the driving speed, which in turn can affect the response time and response error of the control system.

EXPERIMENTAL DATA ACQUISITION

Test methodology

In order to fully study the steering characteristics of the E-HCSS in the steering process, the hydraulic system's hydraulic oil temperature, oil supply pressure and driving speed are selected as the test factors, and the steering response time of the whole steering system operation as well as the response error are taken as the test indexes to carry out the tractor self-driving steering test. In order to test the accuracy of the built steering system, the test is carried out with different frequencies of 1 Hz, 2 Hz and 3 Hz corner inputs, and the corner response curve of the response is obtained as shown in Fig. 4. It can be seen that the system response is accurate and can be used in the study of corner control systems.

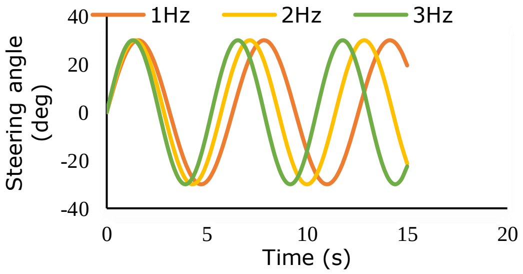


Fig. 4 - Schematic diagram of angle input at different frequencies in the steering system

Test equipment

To analyze the main factors affecting the performance of E-HCSS, a HIL test platform is built (*Xu G et al., 2024*) as shown in Fig. 5. Carsim contains various types of vehicle models with high degrees of freedom, so the tractor model of Carsim was used as a real tractor for data interaction and processing with NI/PXI. Corner tracking control program is written by Matlab/Simulink and compiled into Dspace/MicroAutoBox. The I/O interface of Dspace/MicroAutoBox receives the real signals such as motor current, front wheel angle, steering torque and so on from the sensor of E-HCSS, and drives the PMSM motor according to the final drive signal calculated by the corner controller to realize the steering control (*He X et al., 2022*). The PMSM electric power steering system is installed on the original hydraulic steering system.

The servo motor is used to simulate the steering resistance. The two monitors respectively display the road environment and real-time data. All the interaction data can be obtained from the computer. The key indicator parameters are shown in Table 1.

Fig. 5 - Tractor HIL steering test bench

Table 1

Key parameters of the self-driving tractor E-HCSS test bench

Component modules	Key Parameters	Value
Resistance loading module	Torque loading range	2000 N·m（MAX）
	Torque sensor range	3000 N·m（MAX）
	Torque sensor accuracy	0.5% FS
Hydraulic power module	Maximum assisting pressure	20 MPa
	Pressure sensor range	25MPa（MAX）
	Pressure sensor accuracy	0.25%FS
	Maximum assisted flow	14L/min
	Flow sensor range	25L/min（MAX）
	Flow sensor accuracy	0.5% FS
Electrohydraulic coupling steering module	Maximum torque of the steering motor	240 Nm
	Maximum speed of steering motor	8500 rpm
	Maximum current of steering motor	315 A

In order to realize the operation of the hardware and software systems, the HIL data flow and control structure of the E-HCSS is proposed as shown in Fig. 6.

The tractor model and operating environment model are developed in Carsim 8.02 and embedded into PXI, the path tracking program is written using MatLab2016/Simulink and compiled into MicroAutoBox, the proposed corner controller is run and the current signal is generated by computation, which is sent to the PMSM through the MicroAutoBox real-time module. The PMSM is used to drive the steering system to track the target corner. The tracking error obtained from Carsim8.02 is sent to the controller in the MicroAutoBox through the PXI/NI interface. At the same time, the real-time steering angle from the angle sensor is fed back to the controller through the MicroAutoBox real-time module to complete the closed-loop control (*Xu G et al., 2019*).

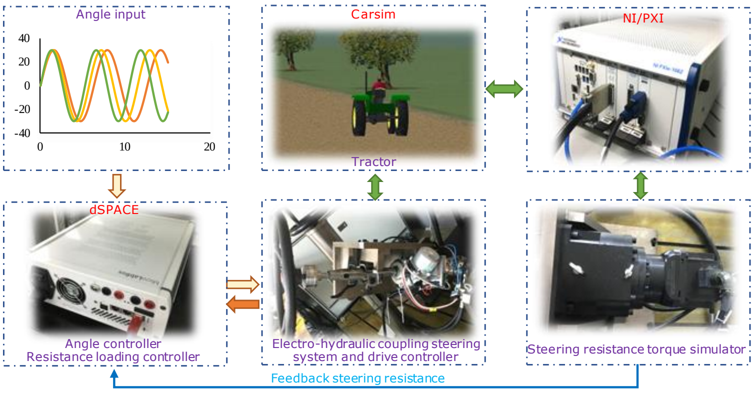


Fig. 6 - The data flow and control architecture of the HIL simulation system

RESULTS

Single factor test

Oil temperature

When the tractor is working, the hydraulic steering system oil temperature will also change with the change of the working load. The temperature change affects the oil flow characteristics and thus affect the steering characteristics of the steering system.

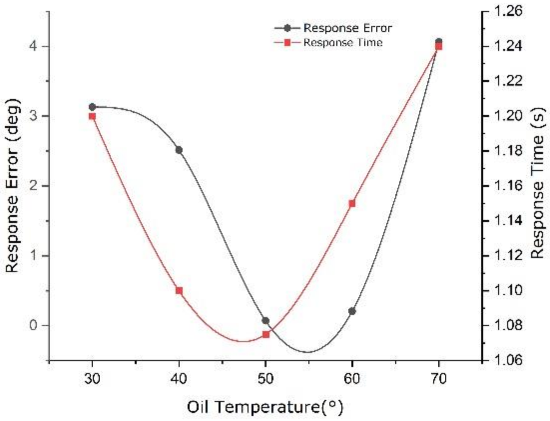
According to (*Yin H et al., 2024*), it is known that the variation range of oil temperature of hydraulic system is generally 30~60°C. Therefore, the gradient of oil temperature variation is designed to be 30°C, 40°C, 50°C, 60°C, and 70°C, respectively. Record the system response time and response error during the autopilot test.

The temperature regulation of the hydraulic oil is carried out by AI-518P artificial intelligence temperature controller, as shown in Fig. 7.

Fig. 7- Artificial intelligence temperature controller

The controller has the function of oil temperature regulation and temperature measurement. Its measurement range is -50~1700°C. The measurement accuracy is 0.25 level, the resolution can be as low as 0.1°C and the response time is less than 0.5 seconds. The regulation mode adopts bit-type regulation and AI artificial intelligence regulation, which contains fuzzy logic PID regulation and parameter self-tuning function. At the same time, the controller is also equipped with an alarm function, which is divided into four ways: upper limit, lower limit, positive deviation and negative deviation.

It can be seen from Fig. 8 that the response error and response time decrease and then increase with the increase of oil temperature. The hydraulic oil of the steering system has higher viscosity and poorer flowability at lower temperatures, thus leading to poorer steering performance of the steering system. As the temperature increases, the viscosity of the oil decreases and the flowability gradually becomes better. Therefore, the steering performance improves, and the response error and response time are minimized at 50~60°C. The temperature continues to rise so that high temperatures lower the viscosity of the hydraulic fluid, increasing the hydraulic system's leakage and causing the hydraulic system's efficiency and response ability to decline. Considering the response time and response error, the oil temperature is 40~60°C for better performance.



Note: Oil supply pressure 12 MPa, driving speed 8 km/h

Fig. 8 - The effect of oil temperature on steering performance

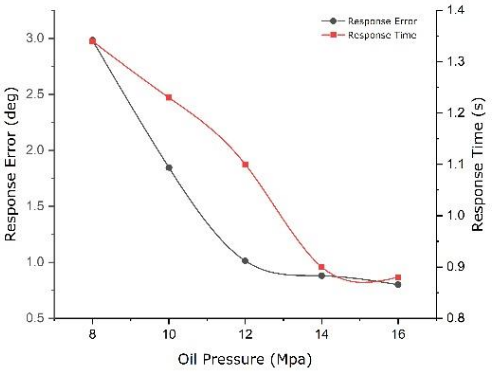
Oil supply pressure

The self-driving tractor will steer in real time according to the change of the path. When facing different steering conditions and steering amplitude, the oil supply pressure should also be changed in real time, and its oil supply pressure has a lot to do with the model and setting of the tractor at the time of production. The oil supply pressure is determined within a certain range once the initial settings of the tractor are determined. However, to better reduce the power consumption while meeting the applicable requirements, further experimental studies on the oil supply pressure are required. The gradient of oil supply pressure change is designed as 8 MPa, 10 MPa, 12 MPa, 14 MPa, 16 MPa. At the same time, the response time and error in the self-driving process are recorded.

MD-S800 series pressure controller is adopted as oil supply pressure regulation which has the advantages of intelligent self-diagnosis, prompting for error types, full-range adjustability of upper and lower limit control points, and simple adjustment methods. The controller has a hydraulic oil supply pressure regulation and pressure display function.

The controller is integrated with pressure measurement, display and control together. When the pressure reaches a predetermined value, the controller controls the controlled equipment to turn on or off to achieve the purpose of automation control. Its pressure range is 0~160 MPa, accuracy level is 1.0 and sampling frequency is 5 Hz.

It can be seen from Fig. 9 that as the oil pressure increases, the system response time and response error are decreasing and the steering performance becomes better. However, after exceeding 14 MPa, with the increase of oil pressure, the performance of the system does not change significantly. This depends on two main reasons. On one hand, the system itself must protect the hydraulic system and the steering system designed for the safety of pressure relief. After reaching a certain pressure, the oil pressure will not be converted into the steering power. On the other hand, there is a constraint in the steering system itself, even if the pressure is increased, it cannot be converted into the actual steering power. Considering the response time and response error, the oil supply pressure of 14~16 MPa has better performance.



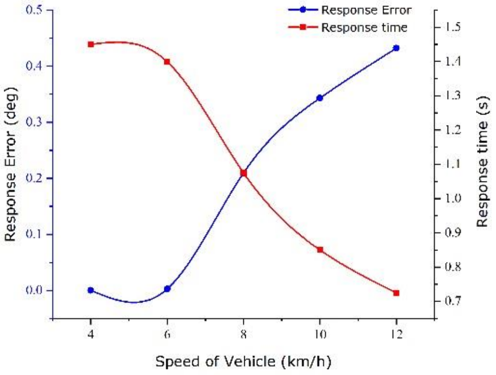
Note: Oil temperature 50°C, driving speed 8km/h

Fig. 9 - The effect of oil temperature on steering performance

Driving speed

Self-driving tractors are generally set to a fixed driving speed during operation. In addition to the power setting of the tractor itself, the driving speed also needs to be combined with the operation scene, and then there is no other reference basis, so that the tractor driving speed does not match the operation conditions frequently (*Liang J et al., 2023; Wu J et al., 2022*). Therefore, in order to find the driving speed that maximizes the performance of the tractor under the corresponding conditions, a single factor test of speed gradient variation was conducted with speed settings of 4 km/h, 6 km/h, 8 km/h, 10 km/h, and 12 km/h. At the same time, the response time and response error of the self-driving process were recorded.

It can be seen from Fig. 10 that the response error of the steering system gradually increases and the response time of the steering system gradually decreases as the vehicle speed increases. The response error and response time are almost unaffected by the change of vehicle speed within 4~6 km/h. At this time, the steering system response error is small at this driving speed. As the speed increases, the response error gradually increases, and the response time gradually decreases. The influence of driving speed on the two indicators has the opposite trend. Considering the response time and response error, better performance can be obtained under the driving speed of 6~10 km/h.



Note: Oil temperature 50°C, oil supply pressure 12 MPa

Fig. 10 - The effect of speed on steering performance

Orthogonal tests

By analyzing the single factor test on the influence of oil temperature, oil supply pressure and driving speed on the steering performance of the E-HCSS, the reasonable range of change is obtained when the steering performance is better: oil temperature 40~60°C, oil pressure 14~16 MPa, driving speed 6~10 km/h.

On this basis, in order to further clarify the optimal parameter combinations of multiple factors, a three-factor, three-level orthogonal test was designed, and orthogonal table $L^9(3^4)$ was selected for the test. Each group of tests was repeated three times, and the factor level design is shown in Table 2. The experimental program and the results are shown in Table 3, with *A*, *B*, and *C* as the values of factor levels.

Table 2

Factors and levels of orthogonal experiment

Level	**Factors**		
	Oil temperature *A* (°C)	Oil pressure *B* (MPa)	Driving speed *C* (km/h)
1	40	14	6
2	50	15	8
3	60	16	10

It can be seen from Table 3 that oil temperature, oil pressure, and driving speed have different degrees of influence on the performance of the steering system. For the metric of response time, the most influential factor is driving speed. Recommended combination level: oil temperature of 60°C, oil supply pressure of 15 MPa, driving speed of 6 km/h. For the index of response error, the most influential factor is the oil temperature, and the recommended combination level is oil temperature of 40°C, oil supply pressure of 14 MPa, and driving speed of 10 km/h.

To further analyze the significance of the effect of each factor on the evaluation indicators, *F*-test (*Chen M et al., 2021*) was performed for each factor using SPSS 26.0 software at a significance level of 0.05, and the analysis of variance is shown in Table 4.

Table 3

Test scheme and results

Serial number		Factor				*T* / s	Δ*e* (deg)
		A	*B*	*C*	Blank column		
1		3	3	1	1	1.38	0.23
2		1	2	3	2	0.94	2.54
3		3	1	3	3	0.96	0.89
4		1	3	2	3	1.09	2.12
5		2	3	3	1	0.89	0.71
6		3	2	2	2	1.15	0.54
7		2	2	1	2	1.35	0.62
8		2	1	2	3	1.01	0.83
9		1	1	1	1	1.39	2.50
t	K_1	3.49	3.36	4.12			
	K_2	3.42	3.44	2.79			
	K_3	3.25	3.36	3.25			
	R	0.08	0.027	0.443			
	Primary and secondary factors *C* > *A* > B						
	Optimal combination $A_3B_2C_1$						
Δ*e*	K_1	1.66	3.06	3.35			
	K_2	7.16	3.7	4.14			
	K_3	2.16	4.22	3.49			
	R	1.833	0.387	0.263			
	Primary and secondary factors *A* > *B* > C						
	Optimal combination $A_1B_1C_3$						

Note: K1~K3 denote the sum of the values under each level of each factor, respectively; R is the extreme deviation

The results show that the effect of driving speed on the response time of the steering system is highly significant at 95% confidence level, and the effects of oil temperature and supply pressure are not significant. The effect of oil temperature on the response error of the steering system is highly significant, and the effect of oil temperature and supply pressure on the response error of the steering system is significant. The primary and secondary factors affecting the response time of the steering system are C, A, and B, and the optimal combination is $A_3B_2C_1$. While the primary and secondary factors affecting the response error of the steering system are A, B, and C, and the optimal combination is $A_1B_1C_3$. The oil temperature and oil supply pressure on the steering system's response time and response error have the same trend, and the driving speed has the opposite trend on the response time and response error. Considering the above laws and focusing on the response time, the optimal parameter combination $A_3B_2C_2$ is determined: the oil temperature is 60°C, the oil supply pressure is 15 MPa, and the driving speed is 8 km/h. The test is repeated five times under the combination and the average is taken. Afterwards, the system response time is 0.88 s, and the response error is 0.54°, which has good steering performance.

Table 4

Variance analysis results

Index	**Variance source**	**Degree of freedom**	**Quadratic sum**	***F* value**	***P* value**
t	*A*	2	0.010	5.785	0.147
	B	2	0.001	0.810	0.552
	C	2	0.304	173.253	0.006**
	Error	2	0.002		
Δ*e*	*A*	2	6.167	1468.254	0.001**
	B	2	0.225	53.587	0.018*
	C	2	0.118	28.206	0.034*
	Error	2	0.004		

Note: $P<0.01$ (highly significant), $0.01<P<0.05$ (significant)

CONCLUSIONS

(1) The dynamics of the E-HCSS of a self-driving tractor were analyzed. Meanwhile, the main factors affecting the performance of the response time and response error were obtained as follows: hydraulic oil temperature, oil supply pressure and driving speed.

(2) By analyzing the influence of hydraulic oil temperature, oil supply pressure and driving speed on the steering performance of the steering system in a single factor test, the reasonable variation range of each factor was obtained in the case of better steering performance: the oil temperature was 40~60°C, the oil pressure was 14~16 MPa, and the driving speed was 6~10 km/h.

(3) Using 3-factor 3-level orthogonal test, it was obtained that the factors affecting the response time of the steering system were: driving speed>oil temperature>oil supply pressure, and the factors affecting the response error were: oil temperature>oil supply pressure>driving speed. The driving speed had opposite influence on the two performance indexes. Taking into account the overall consideration, the optimal parameter combination was determined as follows: oil temperature was 60°C, oil supply pressure was 15 MPa, driving speed was 8 km/h. At this time, the response time of the system was 0.88 s, and the response error was 0.54°. The verification test indicated that under this parameter combination, the steering system had better steering performance. It could provide a reference for the intelligent design of self-driving tractor.

ACKNOWLEDGEMENT

This work was supported by the Youth Project of Natural Science Foundation of Shandong Province (ZR2023QE091), Kccey Research and Development Program of Shandong Province (2022CXPT025); Natural Science Foundation of Shandong Province (ZR2022ME101), Key Laboratory of Vehicle Detection, Diagnosis and Maintenance Technology (JTZL2001), Natural Science Foundation of Shandong Province (ZR2023MF078).

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