

SIMULATION ANALYSIS AND EXPERIMENTAL STUDY OF THE HYDRAULIC SYSTEM FOR AN AUTOMATIC LEVELING PADDY FIELD LAND PREPARATION MACHINE USING AMESim

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基于 AMESim 水田复式整地机液压系统仿真分析与试验研究

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ABSTRACT

Paddy field tillage and soil preparation form the foundation of rice production. To address the low operational efficiency and insufficient leveling accuracy of traditional paddy field preparation equipment, this study developed an automatic leveling control system for paddy field land preparation machinery. The system integrates hydraulic technology with sensors and a microcontroller, using an M 4/3 solenoid directional control valve to achieve automatic leveling. Simulation results obtained using AMESim software indicate that the hydraulic cylinder piston can fully extend within 11 s, demonstrating suitability for the automatic leveling process. Prototype testing further verified that the system operates with stability, safety, and reliability. The implementation of this control system contributes to improving the degree of automation in tillage and land preparation machinery during rice cultivation and supports the advancement of intelligent and information-based agricultural equipment.

摘要

水田耕整地是水稻种植生产的基础, 针对传统的水田耕整地工作效率低, 作业精度低的问题, 本课题组设计研发水田复式整地机自动调平控制系统, 该系统采用机电液一体化技术, 利用液压、传感器、单片机等原件, 通过控制 M 型三位四通电磁换向阀实现水田复式整地机自动调平控制。利用 AMESim 软件对自液压系统进行建模、仿真分析, 仿真结果表明液压系统在 11s 内完成活塞杆行程内伸出动作, 反应快速, 可以应用在自动调平控制系统中。通过样机试验验证自动调平控制系统工作性能稳定, 安全可靠。该水平控制系统有利于提高水稻种植过程中耕整地机械的自动化程度, 助力向信息化发展。

INTRODUCTION

Paddy tillage is a key stage in rice production. Precise tillage enhances the efficiency of water and fertilizer utilization, suppresses weed growth, and ultimately improves rice yield (Aryal *et al.*, 2015; Amin *et al.*, 2021; Sapkal *et al.*, 2019). With the ongoing adjustment of cropping structures and the expansion of rice cultivation in the reclamation areas of Heilongjiang Province, China, traditional implements such as mixers, rakes, and plankers can no longer meet production requirements. These machines are characterized by low operational accuracy, high technical demands on operators, and increased labor intensity (Brown *et al.*, 2013; Cristea *et al.*, 2024; Sun and Yuan, 2021; Xia *et al.*, 2014). Zhou *et al.* (2019) developed a laser-controlled paddy field grading system capable of automatically adjusting the grouting unit and leveling blade to achieve uniform soil leveling. Subsequently, Zhou *et al.* (2020) designed an intelligent rotary tillage grader based on GNSS. In this system, two GNSS antennas were mounted at both ends of the rotary tiller, providing elevation and pitch information. A fuzzy PID control algorithm was used to generate drive voltage signals for an electro-hydraulic proportional directional valve, thereby controlling the hydraulic cylinder extension/retraction. This allowed the implement to rotate about its central axis or move vertically along the guide slot, achieving precise horizontal and vertical adjustments. Gürkan and Tahir (2020) designed a laser-controlled grader in which a PLC-based hydraulic control system was used to improve soil preparation accuracy.

Ali *et al.* (2018) reported that the use of laser land levelers in Pakistan not only improved leveling quality but also reduced water consumption and increased farmers' income. Although these methods enhance operational accuracy, they are generally characterized by complex system structures and high costs.

This study aims to develop an automatic leveling control system to address the low automation level and insufficient operational accuracy associated with traditional paddy field land preparation machinery, while also improving field operation efficiency and quality. Additionally, the performance of the system is analyzed using AMESim software to evaluate the dynamic response, stability, and reliability of the hydraulic system (Cao and Gao, 2011; Chen *et al.*, 2022; Sun *et al.*, 2016; Yeizabet *et al.*, 2022). This approach shortens the development cycle of the automatic leveling control system and provides a data reference for prototype manufacturing.

The test results demonstrate that the automatic leveling control system improves operational accuracy and reduces labor intensity. This study provides technical support for the automation and intelligent development of paddy field land preparation machine, promotes equipment upgrading, and is of significant importance for enhancing the level of agricultural mechanization and accelerating agricultural modernization.

MATERIALS AND METHODS

1. Design of the hydraulic system

The stability of the hydraulic system directly affects the working performance of the automatic leveling paddy field land preparation machinery. Based on the functional requirements identified in this study, the hydraulic system was designed to include a hydraulic pump, flow divider valve, solenoid directional control valve, relief valve, and hydraulic cylinder. The hydraulic circuit of the system is shown in Figure 1. Compared with traditional agricultural implements, the system developed in this study exhibits several advantages. The electromagnetic directional valve controls the hydraulic cylinder to achieve automatic leveling of the dual-operation land preparation machine. The system has a simple structure, stable performance, and includes a relief valve to ensure hydraulic system safety. During operation, the hydraulic pump continuously supplies oil to the automatic leveling control system. When the controller does not output a control signal, the solenoid valve remains in the neutral position, and the hydraulic oil returns to the tank. The controller analyzes the signals from the leveling sensor and issues corresponding electrical commands to control the position of the M 4/3 solenoid-controlled directional valve, thereby changing the flow direction of the hydraulic oil. This adjusts the extension and retraction of the hydraulic cylinder, allowing the frame to rotate around the suspension point to maintain a horizontal working posture. When the system pressure exceeds the preset limit, the relief valve opens, allowing hydraulic oil to flow back to the tank, thus protecting the hydraulic system from overload.

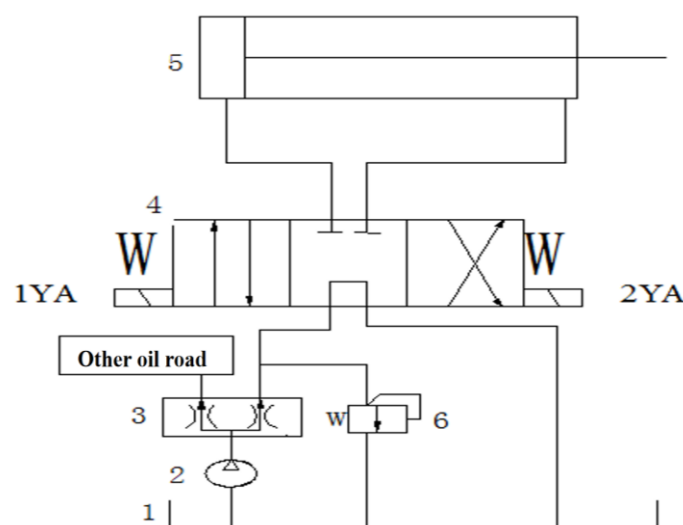


Fig. 1 - Hydraulic system diagram of the automatic leveling control system

1 – Oil tank 2–Hydraulic pump; 3 – Flow divider valve; 4 – Solenoid directional control valve; 5 – Hydraulic cylinder; 6 – Relief valve

2. Modeling and simulated analysis

2.1 Simulated modeling establishment

In this study, the 2014 version of AMESim software is used for modeling and simulation. In the sketch mode, mechanical, hydraulic, and control components were selected from the AMESim component library and connected according to the hydraulic circuit diagram to form a closed hydraulic loop. The operating environment was set to the hydraulic domain (Berzi *et al.*, 2019). The hydraulic system model is shown in Figure 2.

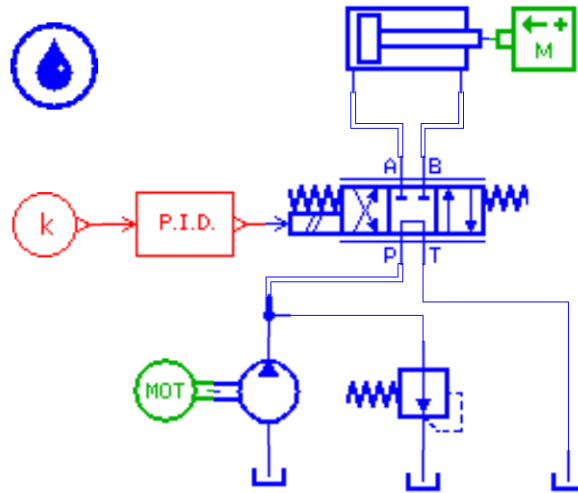


Fig. 2 - AMESim hydraulic simulated model

In the parameter mode, the model parameters are assigned according to the specifications of the selected hydraulic components. The key parameters include pump displacement, rotational speed, relief valve pressure setting, hydraulic cylinder dimensions, and load mass, as shown in Table 1.

Table 1

Hydraulic system parameters	
Item	Parameter
Prime mover speed / (r/min)	1500
Pump speed / (r/min)	1000
Pump displacement / (cm^3/rev)	100
Relief valve pressure / bar	200
Cylinder bore diameter / mm	60
Cylinder piston rod diameter / mm	30
Maximum cylinder stroke / m	0.15
Load mass / kg	1500

2.2 Simulation and analysis of the hydraulic system

In the simulation mode, the operating environment is set to the hydraulic domain. The simulation start time is set to 0 s and the end time to 30 s. The simulation pressure curve is shown in Figure 3, where the X-axis represents time (s) and the Y-axis represents pressure (bar). From 0-3 s, the pressure curve increases in a parabolic trend as hydraulic oil enters the cylinder chamber and the piston rod begins to extend. Between 3-11 s, the pressure stabilizes at approximately 50 bar, indicating that the hydraulic system is operating normally while the piston rod continues to extend. At 11 s, the piston reaches the end of its stroke, resulting in a rapid pressure rise to about 180 bar. Beyond 11 s, the pressure increases slowly, indicating that the relief valve has opened to protect the system by diverting excess hydraulic oil back to the tank, thereby preventing overpressure.

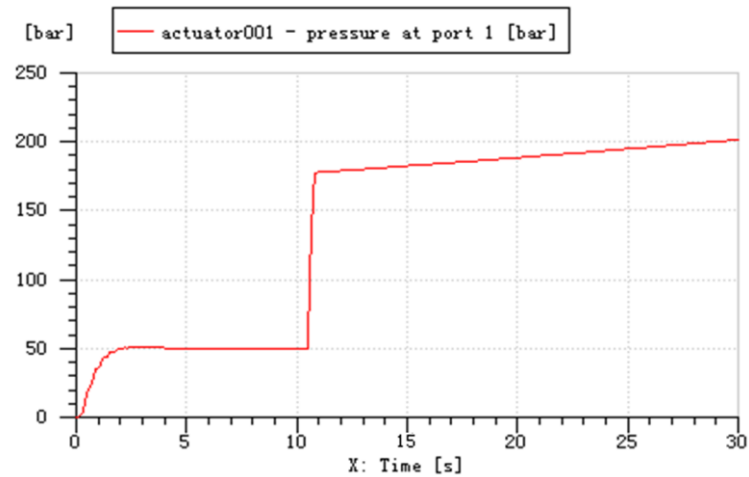


Fig. 3 - Pressure curve of hydraulic cylinder inlet (port 1)

In Figure 4, the X-axis represents time (s) and the Y-axis represents flow rate (L/min). Between 0-3 s, the flow rate curve fluctuates slightly. From 3-11 s, the flow rate increases steadily. At 11 s, the flow rate drops abruptly, and from 11-30 s it remains stable at 0 L/min. During 0-3 s, when the solenoid directional control valve receives the control signal, the valve spool shifts, causing a sudden opening of the flow channel and resulting in a transient pulse in the flow rate at the hydraulic cylinder inlet. Once the 4/3 solenoid directional control valve spool reaches its working position, the pulse disappears and the flow stabilizes. From 3-11 s, the hydraulic system maintains a stable operation, and the flow rate increases smoothly as the piston rod extends, reaching a maximum flow rate of approximately 4.5 L/min. At 11 s, the piston rod reaches the end of its stroke, the cylinder can no longer accept additional oil, and the flow rate drops to 0 L/min. From 11-30 s, the relief valve opens to release excess pressure, returning oil to the tank, and the flow rate remains at 0 L/min.

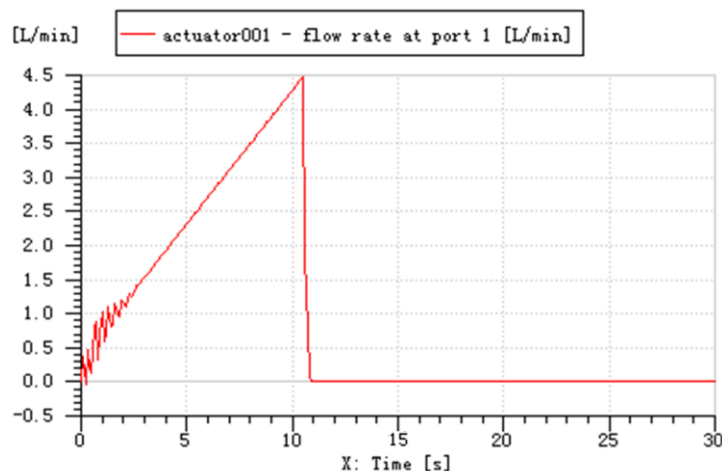


Fig. 4 - Flow rate curve at the hydraulic cylinder inlet (port 1)

In Figure 5, the X-axis represents time (s) and the Y-axis represents pressure (bar). From 0-3 s, the pressure curve rises in a parabolic trend. Between 3-11 s, the pressure remains essentially stable. At 11 s, the pressure drops abruptly, and from 11-30 s it stays at 0 bar. During 0-3 s, when the solenoid directional control valve opens, hydraulic oil is continuously supplied through port 1, causing the pressure in the piston chamber to increase and pushing the piston rod outward. The hydraulic oil in the rod chamber flows out through port 2, where the pressure reaches a maximum of approximately 70 bar. Between 3-11 s, the pressure at port 2 remains stable around 70 bar while the piston rod completes its extension. At 11 s, once the piston rod has fully extended, no additional hydraulic oil can exit the rod chamber, resulting in a sudden pressure drop at port 2 to 0 bar. From 11-30 s, with no further movement of the hydraulic cylinder, the pressure at port 2 remains at 0 bar.

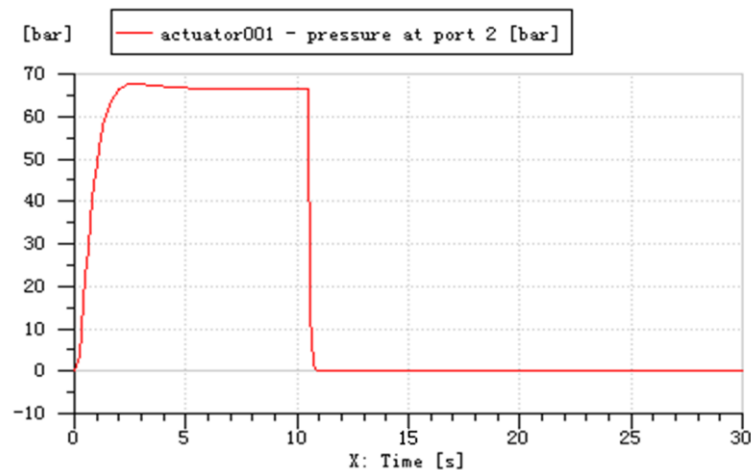


Fig. 5 - Pressure curve at the hydraulic cylinder inlet (port 2)

In Figure 6, the X-axis represents time (s) and the Y-axis represents flow rate (L/s). From 0-3 s, the flow rate curve exhibits slight fluctuations. Between 3-11 s, the flow rate increases steadily. At 11 s, the flow rate drops abruptly, and from 11-30 s it remains stable at 0 L/s. During 0-3 s, when the solenoid directional control valve receives the control signal and begins to shift, the sudden opening of the flow passage causes a transient pulse in the flow at port 2. From 3-11 s, the system operates normally, and hydraulic oil in the piston rod chamber flows steadily through port 2, with a maximum flow rate of approximately 0.055 L/s (3.3 L/min). At 11 s, once the piston rod reaches the end of its extension stroke, no further oil exits the rod chamber, causing the flow rate to drop to 0 L/s. From 11-30 s, the flow remains at 0 L/s as the hydraulic oil is redirected directly back to the tank through the relief path.

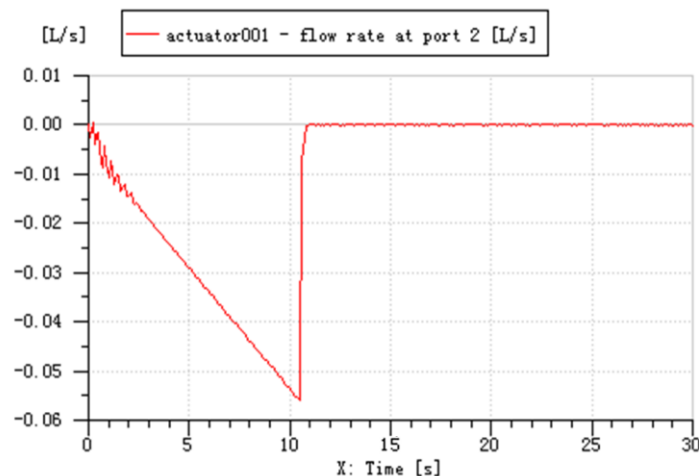


Fig. 6 - Flow curve at the hydraulic cylinder inlet (port 2)

In Figure 7, the X-axis represents time (s) and the Y-axis represents the piston rod extension (m). From 0-11 s, the extension curve increases smoothly, forming an exponential rise pattern. From 11-30 s, the curve remains constant at 0.15 m. During 0-11 s, when the solenoid directional control valve receives the control signal, the flow channel opens and hydraulic oil enters the cylinder through port 1, causing the piston rod to extend at a steady rate. At 11 s, the hydraulic cylinder reaches its maximum extension, with a final stroke of 0.15 m. After 11 s, the control signal remains unchanged and no further relative motion occurs between the piston and the cylinder.

Based on the simulation analysis, the research team established a hydraulic automatic leveling system model using AMESim software. The results indicate that although the hydraulic system exhibits slight pressure fluctuations during operation, it remains generally stable. The safe operating pressure is approximately 70 bar, while the pressure relief setting is 200 bar. Therefore, the hydraulic system should be installed according to the design parameters and applied to the ZD-5.0 paddy field land preparation machine.

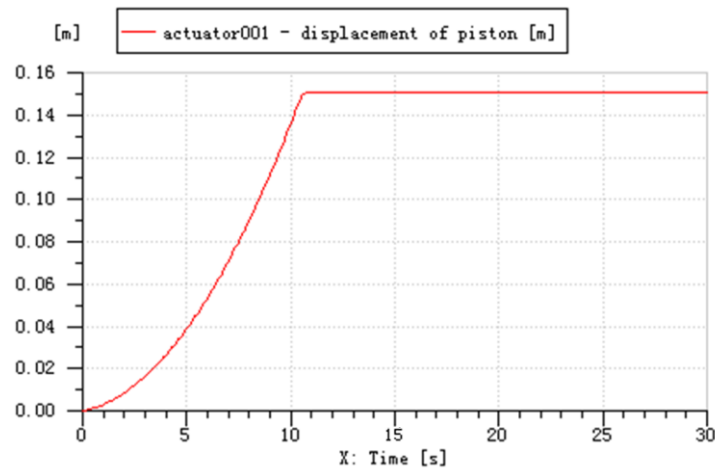


Fig. 7 - Displacement curve of the hydraulic cylinder piston rod

3 Prototype Test

The automatic leveling control system integrates mechanical, hydraulic, automatic control, and sensor technologies, representing a typical application of electro-hydraulic integration in agricultural machinery. Based on the ZD-5.0 paddy field land preparation machine platform, the corresponding hydraulic actuation system was designed, and a level sensor was selected to provide real-time inclination angle feedback. This enables the realization of automatic leveling during land preparation operations. The system consists of the following components: ZD-5.0 paddy field land preparation machine, tractor, onboard computer, controller, hydraulic system, and level sensor. The overall system structure is shown in Figure 8.

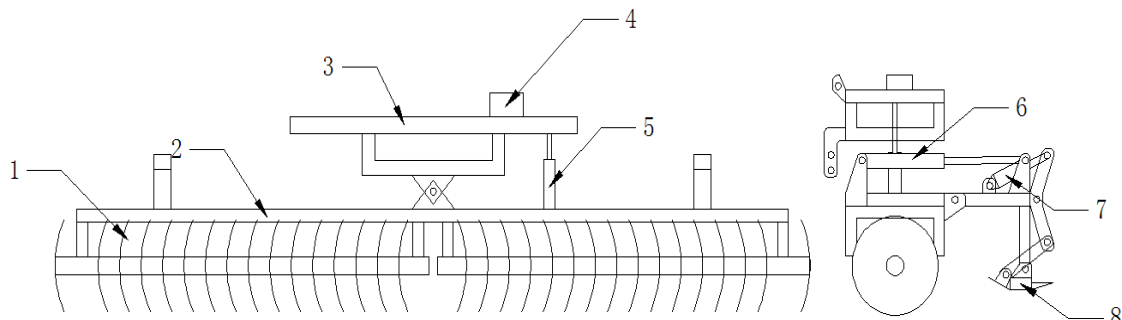


Fig. 8 - Structural diagram of the automatic leveling paddy field land preparation machine.

1 – Land preparation rake blade; 2 – Land preparation machine frame; 3 – Suspension frame; 4 – Integrated hydraulic valve block; 5 – leveling cylinder; 6 – Tail wing plate depth control cylinder; 7 – Angle control cylinder; 8 – Planker

3.1 Test Process

To evaluate the performance of the automatic leveling control system in paddy field land preparation, a leveling accuracy test was conducted at the Daxing Branch of the Heilongjiang Agricultural Reclamation Group in April 2023. The test plot measured 40 m × 80 m. The ambient conditions during the test were: temperature 7°C (283.15 K) and wind speed 2 m/s. A John Deere 904 tractor was used, operating along a serpentine path at a forward speed of 7 km/h. The test field consisted of paddy land plowed in the previous autumn and flooded for three days prior to testing. The prototype test setup is shown in Figure 9. The level (horizon) sensor was mounted on the frame of the land preparation machine. The tractor was operated using a three-point suspension system. As the tractor oscillated laterally during travel, the level sensor detected changes in tilt angle and transmitted real-time signals to the system controller. The controller processed the sensor signals and issued control commands to the M 4/3 solenoid directional control valve, thereby adjusting the direction of hydraulic oil flow. This controlled the extension and retraction of the hydraulic cylinder, causing the frame to rotate around the suspension frame and maintaining a level working posture of the land preparation machine.



Fig. 9 - Test prototype

Test data were collected using a grid sampling method, taking one measurement point every 2 meters across the working plot. The measurements were recorded manually using a custom measuring ruler, with the water surface serving as the reference level. Following a serpentine sampling route, a 20×40 grid was obtained, resulting in 800 measurement points with a point spacing of 200 cm. The average value and standard deviation of the height difference between the water surface and the soil surface after leveling were calculated to evaluate the leveling effectiveness. The field condition prior to testing is shown in Figure 10.



Fig. 10 - Field condition before the test

RESULTS

Farmland flatness (P) is used to quantify the degree of surface fluctuation and reflects the overall smoothness of the field terrain. The standard deviation (S_d) of the vertical elevation deviations between the measured points and the fitted reference surface is used as the evaluation index. A smaller standard deviation (S_d) indicates less surface undulation and therefore better leveling quality. The average deviation of the interpolated elevation points from the fitted surface is calculated as $\bar{d}$:

$$\bar{d} = \frac{1}{N} \sum_{j=1}^N d_j \quad (1)$$

Then the standard deviation value S_d is calculated as follows:

$$S_d = \sqrt{\frac{\sum_{j=1}^N (d_j - \bar{d})^2}{N - 1}} \quad (2)$$

In the formula, d_j represents the elevation difference of the j -th sampling point relative to the water surface (cm); $\bar{d}$ is the mean elevation value of all sampling points (cm); and N is the total number of

sampling points in the field. Based on data processing, the mean elevation after leveling was $\bar{d}=10.44$ cm, and the standard deviation was $S_d=2.13$ cm. Therefore, the leveling accuracy of the paddy field land preparation machine using the horizontal sensor can be controlled within 3 cm, meeting the fundamental agronomic requirements for rice cultivation.

Using MATLAB software (Haas and Peaucelle, 2021; Park and Kim, 2019; Wang et al., 2021; Yan et al., 2019), a contour plot of the field elevation was generated through simple program scripting to visually assess the leveling effect. The application of this leveling control system improves operational accuracy and efficiency, reduces repeated tractor passes, and decreases labor and fuel consumption. Compared with leveling systems based on laser or GNSS control, this system has lower investment cost while still meeting operational requirements.

In Figure 11, both the horizontal and vertical axes represent the number of sampled grid points, and the color gradient represents the elevation relative to the water surface, where the transition from red to blue indicates a change from shallow to deep.

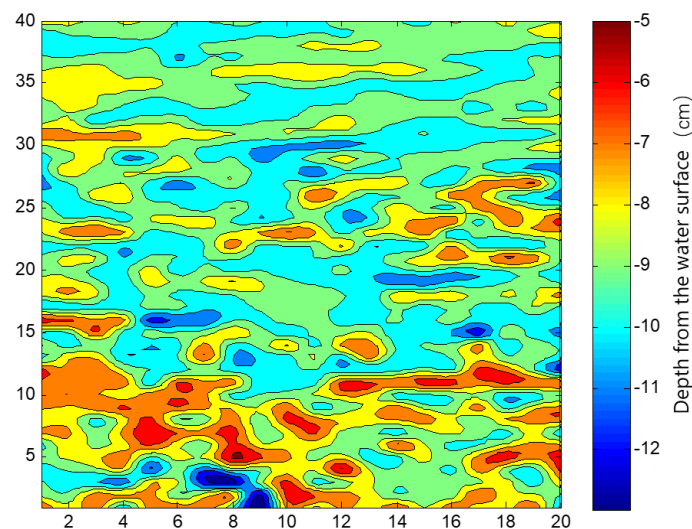


Fig. 11 - Contour plot of field elevation after leveling

CONCLUSIONS

A hydraulic automatic leveling control system for paddy field land preparation machinery was modeled and analyzed using AMESim software. Based on the simulation parameters, a prototype system was developed and mounted on a paddy field land preparation machine for performance testing. The system detects terrain changes through a level sensor and generates corresponding control signals to operate the solenoid directional control valve, thereby adjusting the hydraulic cylinder to maintain a horizontal operating posture.

Field test results show that the leveling accuracy meets agronomic requirements for rice production. After applying the automatic leveling control system developed by Heilongjiang Bayi Agricultural University, the maximum elevation difference was 11 cm, with a standard deviation of 2.13 cm, meeting the standard of fine land preparation. The hydraulic system operated stably and reliably under field conditions.

The proposed horizontal leveling control system has the advantages of simple structure, stable performance, and relatively low cost, effectively reducing operational difficulty and improving land preparation quality. This system has strong application potential for large-scale agricultural use. In future development, the system may be integrated with autonomous driving tractors to achieve unmanned operation. Additionally, combining the level sensor with other control technologies such as laser, GNSS, or RTK can further enhance leveling accuracy, especially in sloped fields or high-standard farmland construction.

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