Development of a crawler chassis attitude adjustment device for a self-propelled maize harvester and experiment of fuselage leveling

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Abstract: Self-propelled maize harvesters are prone to overturning when operating on sloping ground. Solving this problem presents a major technical challenge for researchers. Existing undercarriage leveling technologies are mostly single leveling mechanisms and have a small adjustable angle. A chassis attitude adjustment device has been developed to increase the flexibility of the harvester to slope terrain. The device is made up of a double leveling mechanism and a leveling control system, and it is used to regulate the lateral and longitudinal attitude of the harvester while it is operating. To maintain the attitude of the fuselage within the desired range, the leveling control system regulates the amount of hydraulic cylinder expansion and contraction. The kinematic analysis of the leveling mechanism was done using the vector approach, and the device can be adjusted for lateral and longitudinal inclination between –10° and 17°, and –43.1° and 43.1°, respectively. According to the findings of the static tests, the chassis attitude adjustment device can level the fuselage in four tilt attitudes - 10° uphill, 17° downhill, 25° sideways slope forward, and 25° sideways slope return - with a maximum leveling error of 0.37° and the fastest leveling rate of 0.233 s/(°). For the purpose of evaluating the chassis attitude adjustment performance in the field tests, the tilt inclination of the fuselage was selected as an assessment indicator. The body tilt of the harvester ranged from 0.13° to 1.81° at a harvester speed of 2.5 km/h, with an average body tilt angle of 0.78°, showing that the undercarriage attitude adjustment system was capable of actively leveling the maize harvester attitude. This study enabled the dynamic equilibrium for the maize harvester, which can act as an upstream technology for the design of slope travel devices.

Keywords: crawler harvesters, adjustment mechanism, leveling control systems, vectors method
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1 Introduction

The self-propelled maize harvester has a complex structure and needs to simultaneously perform the operations of walking, cutting, conveying, peeling, and grain gathering[1-3]. The traveling chassis, which is the main structural element of a self-propelled maize harvester, needs to be able to carry all of the operational equipment while also being flexible enough to operate in a variety of scenarios. Wheeled, crawler, and mixed wheeled-crawler constructions are examples of common running chassis. Crawler travel chassis features superior terrain adaption, greater passing capability, and strong grip compared with wheeled structures[4–6]. As a result, crawler travelling chassis has been implemented in a variety of agricultural equipment.

At present, the majority of current crawler maize harvesters in China use classic rigid chassis[7,8]. The chassis frame is made of welded metal. However, the terrain is complicated and has an undulating surface. Stiff chassis do not permit the harvester attitude to be adjusted during working on sloping ground. As a result, the machine tilts with the ground[9,10]. The vehicle barycenter will move to the low potential side as the weight of the grain container rises, increasing the risk of rollover accidents and threatening the lives of the drivers.

In recent years, the safety of harvesters operating on sloping land has attracted the attention of several academics. In order to boost the safety and lateral stability of slope driving, a new three-degree-of-freedom articulated chassis was developed by Zhu et al[11], increasing the maximum inclination for driving by 15.8%. To reduce the final rollover angle of agricultural equipment traveling on complicated roads with slopes, Wang et al.[12] designed an active rollback stability control system based on a single-frame control moment gyro. Geng et al.[13] proposed a retractable track running chassis to decrease the risk of maize harvesters tipping over while operating on slopes. They also increased the safety range of gravity change of the entire machine by adjusting the track wheel distance, which increased the driving stability by 27.34% in challenging terrain conditions. The above research has improved the driving stability. In sloping terrain, harvesters are forced to navigate complicated, uneven production paths. So, it is crucial to level the harvester attitude to increase flexibility.

Chassis leveling technology has been the subject of extensive local and international research. Based on the four-point adjustment

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method, Sun et al.[14] suggested a leveling device for crawler combine harvesters that can modify the side tilt of the machine by 5.17°, enhancing the stance of the machine and hence safety. The adaptive leveling device was designed by Hu et al.[15] to solve the problem of body tilt during operating on uneven terrain. The device is able to perform lateral attitude leveling of ±3.98° and longitudinal attitude leveling of –2.9° to 5.2°, which improves the safety of the machine operation. Jin et al.[16] designed a crawler combine harvester omnidirectional leveling chassis, which can be adjusted for lateral and longitudinal inclination between –5° to 7° and –6.5° to 6.5°, respectively. The device effectively improves slope safety. A pre-detected active leveling chassis for agricultural vehicles was designed by Liu et al.[17,18] with a maximum pitch leveling angle of 2.51° and a maximum side tilt angle of 2.82°. Field tests have shown that the chassis can achieve dynamic leveling within 0.5° accuracy, improving the operational safety of sloping agricultural chassis. In conclusion, chassis leveling technology can effectively level the attitude of the machine and improve operational safety of the harvester.

The US business HILLCO[19] developed a leveling system for mountain combine harvesters. The leveling system was made up of inclination sensors, displacement sensors, hydraulic systems, control systems, etc. The cutting deck can be parallel to the ground and the vehicle l can be leveled at the same time. The self-leveling shoe (SLS) clearing system on the CR9000 series harvester[20] from the New Holland firm in the USA maintained the level of the clearing system on an 8.5° slope, increasing the clearing efficiency of the harvester in an inclined situation. Additionally, undercarriage leveling mechanisms found in crawler combine harvesters made by agricultural machinery manufacturers such as Yanmar[21] and Kubota[22] enable lateral undercarriage leveling, downhill leveling, and uphill leveling, improving the safety of harvester operation.

It is clear from the findings of academics and manufacturers that the leveling devices applied by HILLCO and New Holland[19,20] were able to solve the problem of lateral tilting of fuselages. However, the actual slope of operation was such that both lateral and longitudinal slopes were present at the same time. Researchers proposed a series of leveling techniques[15-18, 21,22] to solve the problem of lateral and longitudinal tilting of fuselages. The above leveling technology concentrates on undercarriage leveling devices for harvesting machinery, which regulate the attitude of the machine body through hydraulic cylinders, leveling components, and control systems to improve operational safety. The leveling devices are all single-level mechanisms and complex in construction, and longitudinal and lateral leveling inclination are small owing to movement interference of the mechanism. Therefore, this study proposes a chassis attitude adjustment device with a double leveling mechanism. It is used to regulate the lateral and longitudinal attitude of the harvester while it is operating. Each layer mechanism levels the fuselage independently, reducing interference between key components and increasing the leveling inclination. The leveling performance of the device was verified by test.

2 Materials and methods

2.1 Design of chassis attitude adjustment device

2.1.1 Necessity analysis of fuselage slope attitude adjustment

Crawler maize harvesters are susceptible to tipping when operating on uphill, downhill, or sideways slopes. A stress analysis was conducted for a harvester operating on a sloping field. In *yoz* plane, points k_1 and k_2 represent the front and rear edge pressure points where the harvester chassis contacts the crawler grounding section. When the harvester moves at a constant speed up or down a slope, an excessively steep pitch angle can cause the chassis to tip either backward or forward around point k_2. Based on the geometric relationship shown in Figure 1, the critical tipping angle for a harvester operating on a longitudinal slope can be determined as shown in Equation (1).

$$\begin{cases} \alpha_{\lim U} = \arctan\left(\dfrac{N_{k_2} l^2}{2mgH\cos\alpha\cos\beta} - \dfrac{l}{H} - \tan\alpha\right) \\ \alpha_{\lim D} = \arctan\left(\dfrac{2l}{H} - \dfrac{N_{k_2} l^2}{2mgH\cos\alpha\cos\beta} + \tan\alpha\right) \end{cases} \tag{1}$$

where, $\alpha_{\lim U}$ and $\alpha_{\lim D}$ are the critical tipping angles of a harvester driving uphill and downhill respectively, (°); H is the vertical distance from the harvester gravity center to slope, mm; l is the length of crawler track in contact with ground, mm; B is the track gauge, mm; α is the longitudinal angle of slope, (°); β is the lateral angle of slope, (°); N_{k1} and N_{k2} are the front and rear edge pressures, respectively, of the track ground-contacting surface, N.

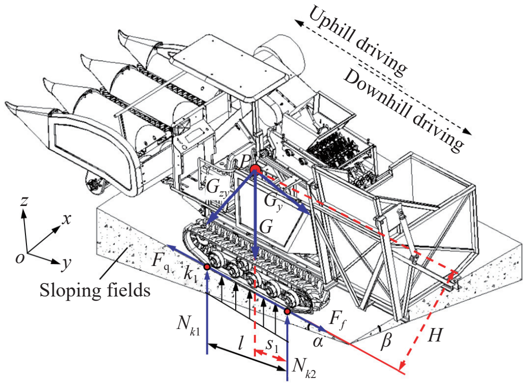


Figure 1 Force analysis of crawler-type maize harvester on longitudinal slope

In the *xoz* plane, points K_3 and K_4 represent the lateral center points of the left and right crawler ground contact sections of harvester chassis, respectively. A steep side slope can easily cause the harvester to tip over around point K_3 or K_4. As shown in Figure 2, the left and right support forces of the crawler chassis are expressed by Equation (2):

$$\begin{aligned} F_{N_1} &= \int_0^l \frac{1}{l}[N_{k_1} l + (N_{k_2} - N_{k_1})x]\mathrm{d}x \\ F_{N_2} &= \int_0^l \frac{1}{l}[N_{k_2} l + (N_{k_1} - N_{k_2})x]\mathrm{d}x \end{aligned} \tag{2}$$

Based on the geometric relationships in Figure 2 and in conjunction with Equation (2), the critical tipping angle of the harvester when moving laterally on a slope can be determined, as

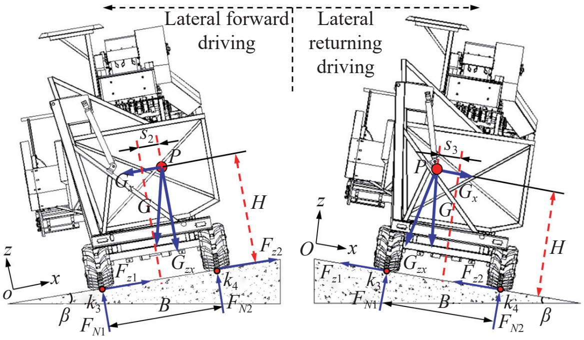


Figure 2 Force analysis of crawler-type maize harvester on lateral slope

shown in Equation (3):

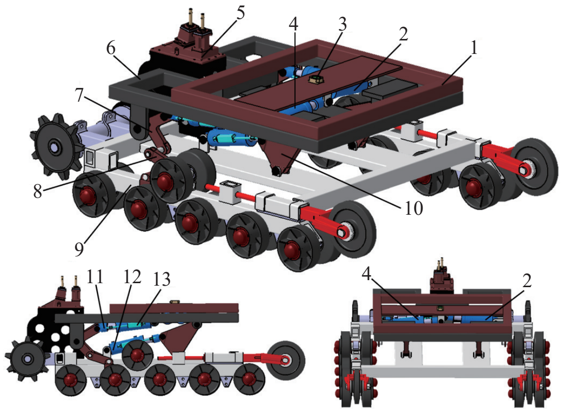
$$\begin{cases} \beta_{\lim F} = \arctan\left(\tan\beta + \dfrac{B\displaystyle\int_0^l \frac{1}{l}[N_{k_2}l + (N_{k_1} - N_{k_2})x]\mathrm{d}x}{mgH\sin\alpha\cos\beta}\right) \\ \beta_{\lim R} = \arctan\left(\tan\beta + \dfrac{B\displaystyle\int_0^l \frac{1}{l}[N_{k_1}l + (N_{k_2} - N_{k_1})x]\mathrm{d}x}{mgH\sin\alpha\cos\beta}\right) \end{cases} \tag{3}$$

where, $\alpha_{\lim F}$ and $\alpha_{\lim R}$ are the critical tipping angles of the harvester driving lateral forward and returning, respectively, (°).

Analyzing Equations (1) and (3), when the harvester operates on a slope, the structure of its crawler chassis remains unchanged, meaning that the track gauge, crawler ground contact length, and body mass are constants. However, due to the harvester's asymmetric design, changes in the fuselage posture will affect the position of the center of gravity (P), subsequently altering the parameter H and ultimately impacting the critical tipping angle of the fuselage. Based on this analysis, designing a chassis attitude adjustment device is essential for enhancing harvester performance on slopes.

2.1.2 Structure and composition

The chassis attitude adjustment device is a double-layer frame structure, including the upper leveling mechanism (leveling lateral attitude of fuselage) and the lower leveling mechanism (leveling longitudinal attitude of fuselage), as shown in Figure 3. The left side hydraulic cylinder, the right side hydraulic cylinder, and the upper suspension form the upper leveling mechanism. The left and right side hydraulic cylinders were mounted opposite to each other on the upper suspension. The lower leveling mechanism consists of the lower suspension, upper linkage, lower linkage, leveling plate, front hydraulic cylinder, and rear hydraulic cylinder. The front hydraulic cylinder was mounted on the lower suspension. The rear hydraulic cylinder was mounted on the chassis frame. The lower linkage was connected to the chassis frame and the upper linkage. The upper linkage was connected to the upper suspension and the front hydraulic cylinder. An attitude sensor (Shenzhen Witte Intelligent Technology Co., LTD., China) was mounted in the center of each suspension to monitor tilt inclination of the fuselage. Each hydraulic cylinder was connected to a linear displacement sensor. The detailed parameters of the chassis attitude adjustment device are listed in Table 1.



1. Upper suspension 2. Right side hydraulic cylinder 3. Attitude sensor 4. Left side hydraulic cylinder 5. Transmission 6. Lower suspension 7. Upper linkage 8. Lower linkage 9. Crawler chassis 10. Leveling plate 11. Front hydraulic cylinder 12. Rear hydraulic cylinder 13. Linear displacement sensor

Figure 3 Structure diagram of chassis attitude adjustment device

Table 1 Comparison of model prediction results

Technical parameters		Parameter value
Upper leveling mechanism	Length of upper linkage/mm	l_1=220, l_2=220
	Length of lower linkage/mm	l_3=220
	Length of leveling plate/mm	l_4=137, l_5=217, l_6=213
	Initial length of front and rear hydraulic cylinders/mm	520
	Angle range of fuselage pitch leveling/(°)	–10-17
Lower leveling mechanism	Initial length of right and left hydraulic cylinders/mm	520
	Angle range of fuselage roll leveling/(°)	–43.1-43.1
	Length of track contact/mm	1470
	Track width/mm	280
	Track gauge/mm	1260
	Maximum load of chassis/kg	4500
	Minimum ground clearance of chassis/mm	280

2.1.3 Working principle

The harvester tilts in the longitudinal direction while traveling uphill (shown in Figure 4b) or downhill (shown in Figure 4c), and tilts in the lateral direction while traveling forward (shown in Figure 4e) or back (shown in Figure 4f) on the side slope. The longitudinal tilt attitude of the fuselage is adjusted by the lower leveling mechanism. When the harvester is traveling uphill, the front hydraulic cylinder is extended to drive the upper linkage to rotate counterclockwise around point A_0, as shown in Figure 4b, while the lower linkage rotates counterclockwise around point B_0. The rear hydraulic cylinder is shrunk and drives the leveling board to rotate counterclockwise around point C_0. The fuselage is brought to a horizontal attitude under the lower leveling mechanism. Similarly, when the harvester travels downhill, as shown in Figure 4c, the front hydraulic cylinder is shrunk while the rear hydraulic cylinder is extended, driving the upper and lower linkage and leveling plate to rotate clockwise around their respective center of rotation until the body is adjusted to a horizontal attitude.

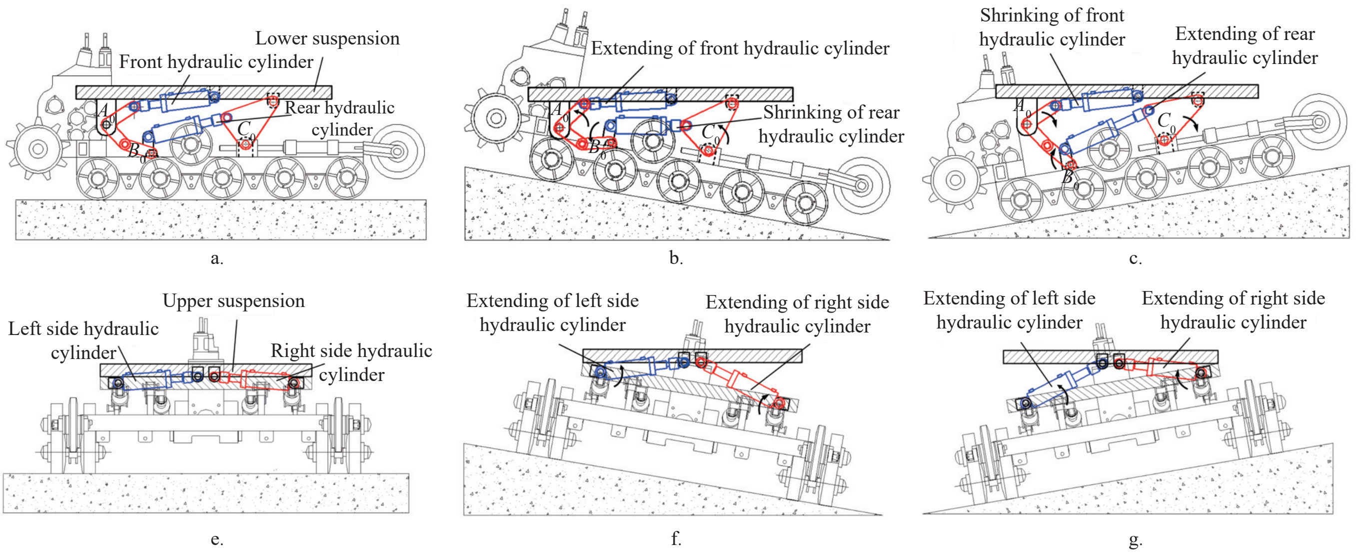
The longitudinal tilt attitude of the fuselage is adjusted by the lower leveling mechanism. When the harvester is traveling forward on a side slope, the attitude of the fuselage is left-high and right-low, as shown in Figure 4f. The right and left hydraulic cylinders are the driving part and driven part, respectively, and both of the hydraulic cylinders are extended to bring the body into a counterclockwise horizontal attitude. When the harvester travels back on a side slope, its fuselage is left-low and right-high. The left and right hydraulic cylinders are the driving part and driven part, respectively, and the fuselage is leveled counterclockwise, as shown in Figure 4g.

It should be noted that each hydraulic cylinder is assembled into the device with a specific initial length. During harvester operation, whether adjusting the longitudinal or lateral posture, the hydraulic cylinders must be paired for synchronized movement to ensure smooth leveling.

2.2 Design of attitude adjustment control system

2.2.1 Mathematical models

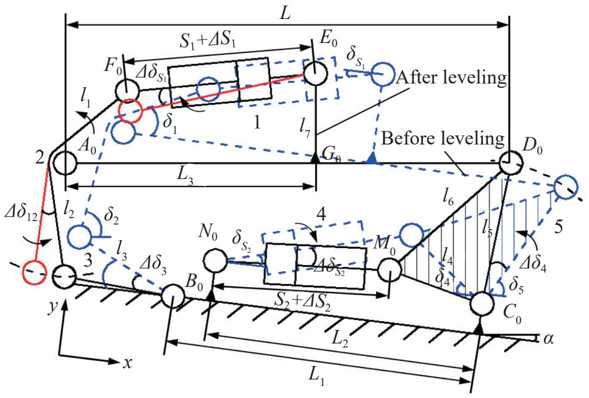
The kinematic relationships among the components in each leveling mechanism are analyzed, and the relationship between the variation of the hydraulic cylinders and the slope inclination (longitudinal and lateral inclination) is solved for the subsequent precise design of the leveling control system. As shown in Figure 5, the preleveled and post-leveled states of lower suspension are seen in the blue and black parts, respectively. All parts of the mechanism have angular and displacement changes in the leveling process. The x-axis is created in the direction of longitudinal slope and the y-axis



a. b. c.

e. f. g.

Figure 4 Working principle of chassis attitude leveling device



Note: 1. Front hydraulic cylinder 2. Upper linkage 3. Lower linkage 4. Rear hydraulic cylinder 5. Leveling plate 6. Lower suspension

Figure 5 Analysis of pitch-leveling kinematics

is created perpendicular to the direction of the slope. The vectorial analytical method[23,24] is used to analyze movement relations of the mechanism. The vector equations for the three vector closed polygons ($A_0F_0E_0G_0$, $N_0M_0C_0$, $A_0D_0C_0B_0$) are created and expanded by the Taylor Formula, as shown in Equation (4):

$$\begin{aligned}
&l_1\cos(\delta_1+\Delta\delta_{12})+(S_1+\Delta S_1)\cos(\delta_{S_1}+\Delta\delta_{S_1})=L_3\cos\alpha+l_7\cos\left(\frac{\pi}{2}+\alpha\right)\\
&l_1\sin(\delta_1+\Delta\delta_{12})+(S_1+\Delta S_1)\sin(\delta_{S_1}+\Delta\delta_{S_1})=L_3\sin\alpha+l_7\sin\left(\frac{\pi}{2}+\alpha\right)\\
&(S_2+\Delta S_2)\cos(\delta_{S_2}+\Delta\delta_{S_2})+l_4\cos(\delta_4+\Delta\delta_4)=L_2\\
&(S_2+\Delta S_2)\sin(\delta_{S_2}+\Delta\delta_{S_2})+l_4\sin(\delta_4+\Delta\delta_4)=0\\
&l_2\cos(\delta_2+\Delta\delta_2)+l_3\cos(\delta_3+\Delta\delta_3)+L\cos\alpha+l_5\cos(\delta_5+\Delta\delta_4)+L_1=0\\
&l_2\sin(\delta_2+\Delta\delta_2)+l_3\sin(\delta_3+\Delta\delta_3)+L\sin\alpha+l_5\sin(\delta_5+\Delta\delta_4)=0
\end{aligned}\tag{4}$$

where, l_1 is the length of the front end of the upper linkage, mm; L_3 is the horizontal distance between the upper linkage articulation point and the end of the front hydraulic cylinder, mm; l_7 is the horizontal distance between the end of the front hydraulic cylinder and the lower suspension, mm; L_2 is the distance between the hinge point of the front end of the rear hydraulic cylinder and the hinge point of the adjusting plate along the x-axis, mm; l_2 is the length of the lower end of upper linkage, mm; l_3 is the length of lower linkage, mm; l_4–l_6 are the three side lengths of the leveling plate, mm; S_1+ΔS_1 is the length of the front hydraulic cylinder, mm; S_2+ΔS_2 is the length of the rear hydraulic cylinder, mm; δ_1+$\Delta\delta_{12}$, δ_{S1}+$\Delta\delta_{S1}$, δ_{S2}+$\Delta\delta_{S2}$, δ_2+$\Delta\delta_2$, δ_3+$\Delta\delta_3$, and δ_5+$\Delta\delta_4$ are the angle of rotation of the corresponding part in Figure 5, mm; α is the longitudinal angle of the slope, (°).

Equation (4) can be simplified as an expression for the amount of variation in the front and rear hydraulic cylinders during leveling.

$$\begin{aligned}
S_1+\Delta S_1&=\sqrt{\begin{aligned}&L_3^2+l_7^2-2l_1[\cos(\delta_1+\Delta\delta_{12})(L_3\cos\alpha+l_7\cos\alpha)]+\\&\sin(\delta_1+\Delta\delta_{12})(L_3\sin\alpha+l_7\sin\alpha)]+l_1^2\end{aligned}}\\
S_2+\Delta S_2&=\sqrt{L_2^2+l_4^2-2L_2l_4\cos(\delta_4+\Delta\delta_4)}
\end{aligned}\tag{5}$$

where, δ_4+$\Delta\delta_4$ is the rotational angle of the corresponding part in Figure 5, (°).

The research on the chassis attitude adjustment device relied on the 4YZL-3 crawler-type maize combine harvester. The length of the chassis is 1192 mm, and its width is 1410 mm. The chassis frame is linked to the bottom of lower linkage. The diameter of the pulley is 400 mm, and the distance between the pulley center and the left end of the chassis is 780 mm. The distance between the lower link and the left end of the frame was determined to be 550 mm based on the size of the pulley. After the upper suspension has been leveled, the position of the components is shown in Figure 6. At this point, the position relationship between the components of the lower leveling mechanism satisfies Equation (6):

$$\begin{aligned}
&l_1\sin\delta_1+l_2\sin\delta_2+l_3\sin\delta_3=(h-400)\cos\alpha\\
&l_5\sin\delta_5\cos\alpha=h-400
\end{aligned}\tag{6}$$

where, δ_1, δ_2, δ_3, and δ_5 are the position angles of the corresponding part in Figure 5, (°); h is the vertical distance of the lower suspension from the slope before leveling, mm.

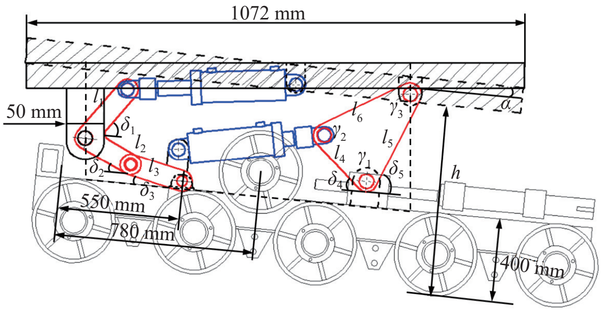


Figure 6 Analysis of pitch-leveling kinematics

When the upper and lower linkages are moved to their limit positions, l_2 and l_3 are in a straight line. To avoid interference between the lower suspension and the front end of the chassis frame and to maximize the rotational range of the leveling linkage, the leveling lower linkage l_3 was taken to be 220 mm. Both l_1 and l_2 were taken to be 220 mm, and the angle between them was 90°[25]. In this state, the angles δ_2, δ_3, and δ_1 were obtained analytically as 21°, 21°, and 69°, respectively. Ultimately, the expression for l_5 is obtained as shown in Equation (7):

$$l_5 = \frac{363.1}{\sin\delta_5 \cos^2\alpha} \tag{7}$$

where, l_5 can be calculated according to the cosine theorem, mm.

The maximum mass of the harvester at full load is 4280 kg. In order to meet the load-bearing requirements, a hydraulic cylinder (produced by Shandong Hengdingsheng Hydraulic Machinery Co., Ltd., China, with a range of 200 mm and an initial length of 520 mm) was selected. This hydraulic cylinder can carry 5 t. The lengths of L_2, L_1, L_3, l_7, and L are 725 mm, 755 mm, 506 mm, 52 mm, and 1072 mm, respectively, according to the rationalization of the installation and commissioning of the device. Based on the rotational limit positions of the upper and lower linkage and the length of lower suspension, the lengths of the leveling plates l_4 and l_5 could be determined as 137 mm and 217 mm, and the angle γ_1 as 70°. According to the cosine theorem, the length of l_6 can be obtained as 213 mm. Then, the angle γ_2 can be found as 73° and the angle γ_3 as 37°. In summary, the downhill leveling limit of 17° can be obtained when the upper and lower linkage are in a straight line. If the upper and lower linkage do not interfere with the chassis frame, the uphill leveling angle is 10°.

$$\begin{aligned} S_1 + \Delta S_1 &= 22.8\sqrt{497.1 - 168.9\cos\alpha + \sin\alpha} \\ S_2 + \Delta S_2 &= 445.7\sqrt{2.74 - \cos\left[110^\circ - \arcsin\frac{1.67}{\cos^2\alpha}\right]} \end{aligned} \tag{8}$$

In the upper leveling mechanism, the left and right hydraulic cylinders are hinged to the leveling lower and upper suspensions, respectively. The attitude of the harvester moving forward on a side-slope is shown in Figure 7. The left and right hydraulic cylinders are the leveling driven components. The x-axis was created along the direction of the side slope and the y-axis was created perpendicular to the side slope. The vector equations for the closed polygon ($P_0H_0I_0Q_0$) were created and expanded by the Taylor Formula:

$$\begin{aligned} &(S_3 + \Delta S_3)\cos(\delta_{S_3} + \Delta\delta_{S_3}) + l_8\cos\beta + (S_4 + \Delta S_4)\cos[\pi - \\ &\quad (\delta_{S_4} + \Delta\delta_{S_4})] = L_3 \\ &(S_3 + \Delta S_3)\sin(\delta_{S_3} + \Delta\delta_{S_3}) + l_8\sin\beta + (S_4 + \Delta S_4)\sin[\pi - \\ &\quad (\delta_{S_4} + \Delta\delta_{S_4})] = 0 \end{aligned} \tag{9}$$

where, L_3 is the distance between the end articulation points of the left and right hydraulic cylinders, mm; l_8 is the distance between the hinge points of the left and right hydraulic rods, mm; S_3+ΔS_3 and S_4+ΔS_4 are the length of the left and right side hydraulic cylinders, mm; δ_{S3}+$\Delta\delta_{S3}$ and δ_{S4}+$\Delta\delta_{S4}$ are the rotation angle of the left and right side hydraulic cylinders, mm.

The upper suspension is the same width as the lower suspension (L'=1210 mm) to prevent interference with the tracks when the device is moving. Square torque tubes that have been welded together make up the upper suspension. The articulation point of the hydraulic cylinder was measured inside the suspension, and L_3 was 1110 mm. The specifications of the left and right side hydraulic cylinders were the same as the front and rear hydraulic cylinders. To ensure that the hydraulic cylinder was easily retracted during leveling movements, S_3+ΔS_3 and S_4+ΔS_4 were both 620 mm, and l_8 was 58 mm. Based on the cosine inverse trigonometric function, the initial mounting angles δ_3 and δ_4 of the hydraulic cylinder were 31.9°. The obtained parameters were brought into Equation (9) to obtain the relationship between the hydraulic cylinder and the lateral inclination, as shown in Equation (10). The active hydraulic cylinder adjusts the extension to its maximum value, and the limit lateral leveling inclination is –43.1° to 43.1° by the cosine inverse trigonometric function.

$$\begin{aligned} S_3 + \Delta S_3 &= 652.9 - 34.1\cos\beta - 54.7\sin\beta \\ S_4 + \Delta S_4 &= 652.9 - 34.1\cos\beta + 54.7\sin\beta \end{aligned} \tag{10}$$

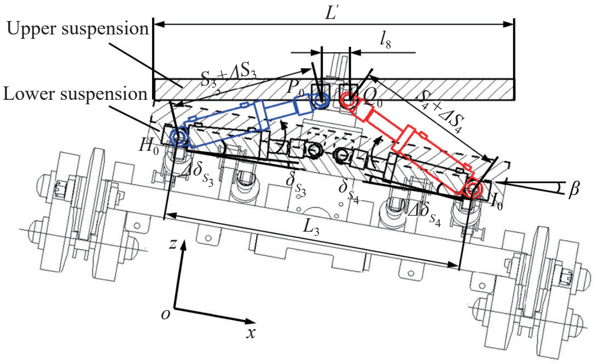
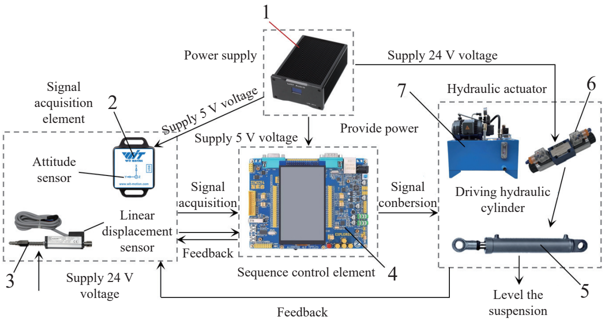


Figure 7 Analysis of cross-roll leveling kinematics

2.2.2 Design of the control system

The attitude leveling control system ensures the attitude stability of the fuselage by adjusting the attitude of the upper and lower suspension, which mainly includes the controller, DC power supply, displacement sensor, attitude sensor, solenoid valve, and hydraulic cylinder, as shown in Figure 8. The dual voltage outputting power supply (24 V/5 V) provides 24 V DC for the solenoid valve and displacement sensor, and 5 V DC for the controller and attitude sensor. The attitude sensor is used to monitor the tilt angle of the suspension and output the signal to the controller. The displacement sensor is used to monitor the displacement of the hydraulic cylinder and output the signal to the controller. The controller receives the monitoring signal of the attitude sensor and displacement sensor, and outputs the control signal of the solenoid valve. The solenoid valve regulates the expansion and contraction of the hydraulic cylinder according to the output signal from the controller. The technical details are listed in Table 2.



1. DC power supply 2. Attitude sensor 3. Linear displacement sensor 4. STM32 microcontroller 5. Leveling hydraulic cylinder 6. Solenoid directional valve 7. Hydraulic station

Figure 8 Hardware components of the chassis attitude leveling control system

Table 2 Instrument technical details

Instrument	Type	Manufacturer	Range	Accuracy
Microcontroller	STM32F4072G	Guangzhou Starwing Electronic Technology Co., Ltd., Guangzhou City	/	/
Attitude sensor	BWT61CL	Shenzhen Witte Intelligent Technology Co., LTD. Country: China	X, Z Axis: ±180° Y Axis: ±90°	X, Y Axis: 0.1° Z Axis: 1°
Solenoid-directed valve	4WE6F61B/CG24N9Z5L	Beijing Huade Hydraulic Industry Group Limited Liability Company, Beijing, China	0-31.5 MPa	0.1 MPa
Displacement Sensor	KTR-200	Shenzhen Hongmai Technology Co., Ltd., Shenzhen, China	0-200 mm	0.01 mm

The chassis attitude adjustment device controls the harvester body's longitudinal and lateral leveling in the same manner. The longitudinal leveling control method is used as an example to illustrate this, with the control system flow shown in Figure 9. When the program begins, it first sets the target leveling angle α_0 for lower suspension (target angle is 0°), the target angle error $\Delta\alpha$ for the suspension leveling control system, and the front and rear hydraulic cylinder length thresholds ΔS_E. During the leveling operation of the lower mechanism, the attitude sensor continuously receives real-time attitude data of the lower suspension. If the difference between actual pitch angle α and target angle exceeds the target angle error, the hydraulic actuator adjusts the posture of the lower suspension. The target change amount for the front and rear hydraulic cylinders is calculated using Equation (8). A linear displacement sensor moves synchronously with the hydraulic cylinder to monitor its actual displacement. The system checks if the difference between the target and actual values falls within the hydraulic cylinder length threshold ΔS_E. If it does not, the hydraulic cylinder length is adjusted accordingly. When the actual displacement of the hydraulic cylinder is positive, the microcontroller outputs a voltage signal to control the opening direction of the electromagnetic reversing valve, which shortens the hydraulic cylinder; otherwise, it extends the cylinder, thereby forming a closed-loop control within the hydraulic actuator. If the difference between actual pitch angle and target angle is smaller than the target angle error, the hydraulic actuator remains inactive, and the system control concludes.

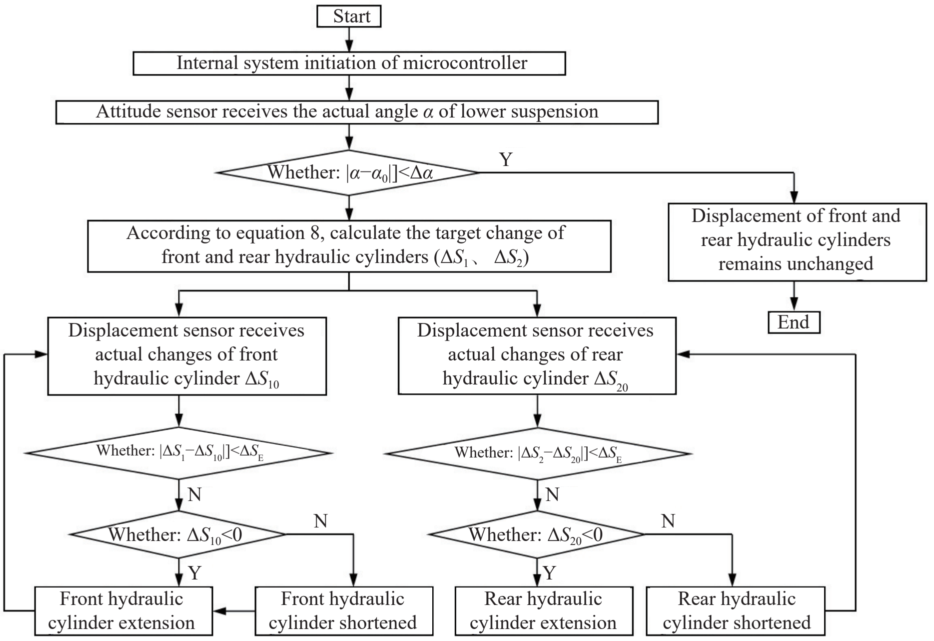


Figure 9 Flow chart of the pitch attitude control system

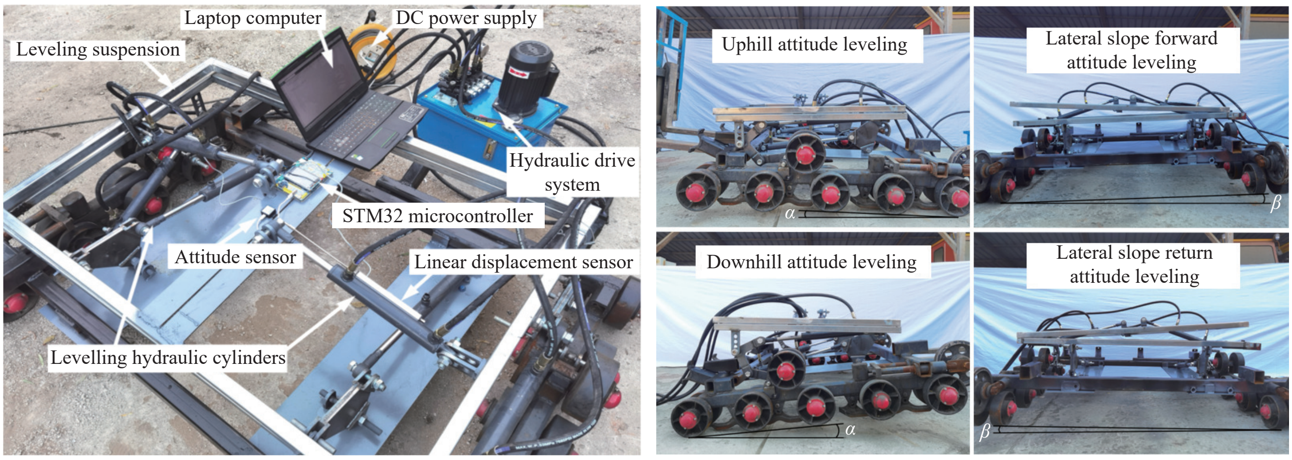
2.3 Experiments and measurements

2.3.1 Static leveling test site and method description

Static and dynamic leveling tests were carried out to verify the leveling performance of the chassis attitude adjustment device. Static tests were conducted at Nanling Campus of Jilin University on 22 August 2022. The test site was a concrete floor with a flat, untiled surface. The chassis attitude adjustment device is shown in Figure 10a. In the static test, the chassis was not driven and the leveling system was operated. Before the test, the chassis was lifted with a forklift from the front ends, rear ends, left ends, and right ends to create a longitudinal and a lateral inclination. The longitudinal and lateral leveling tests were carried out separately. The automatic leveling function of the system was switched on, and the suspension was adjusted from each of the four tilted states to the horizontal state. The leveling test was completed when the suspension was stabilized, as shown in Figure 10b. It is worth noting that the device had a lateral leveling limit inclination of –43.1° to 43.1°, but sloping terrain greater than 25° was not suitable for growing crops[26,27]. The starting inclination for lateral leveling was ±25°. The limit longitudinal leveling inclination of the device was –10°-17°, so the uphill stance was leveled from –10°, and the downhill stance from 17°.

2.3.2 Field test site and method description

The field test was conducted in Mu Shihe Village, Jiutai District, Changchun City, Jilin Province (126°10′E, 44°23′N). This study site belongs to the continental seasonal climate, and is located at the transition from the wet zone to semi-arid zone. The longitudinal inclination of the test site was 10°, and the lateral inclination was 7°. The field tests lasted from 8 to 16 October 2022 (from the second week to the third week after maize harvest), with average daily temperatures of 12.2°C-15.7°C. 4YZL-crawler maize combine harvester (Jilin Nongxin Machinery Manufacturing Co., Ltd.) with the chassis attitude adjustment device was tested, as shown in Figure 11.



a. Chassis attitude adjustment device b. Different posture adjustments of the device

Figure 10 Static leveling test

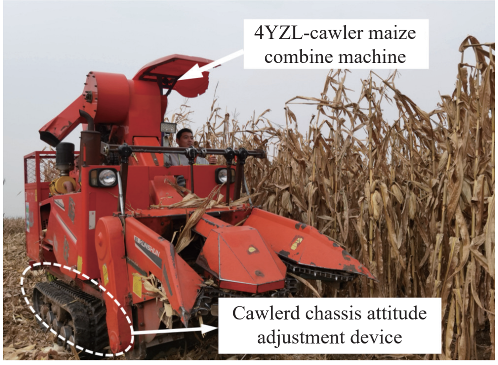


Figure 11 Field test

Field tests required recording the tilt inclination of the fuselage with and without the leveling procedure on. Maize harvester forward speed was 2.5 km/h. The trial field was split into several test areas. Each test area was 95 m in length and 4 m in width. Each test area was divided into three sections: the first (5 m in length) was the preparation area, the second (85 m in length) was the test area, and the third (5 m in length) was the finishing area. In each test, the maize harvester traveled for 120 s. The harvester ran two kinds of tests: one with the leveling program off, and the other with the leveling program on. Each kind of test was repeated three times at the same test distance and driving speed, and the test data was recorded.

2.3.3 Test indices

In static tests, the leveling error[28], leveling rate[29], and root mean square of leveling error in the longitudinal and lateral attitude of the chassis[30] need to be measured. The measurement methods of each indicator are as follows:

1) The leveling error is determined by calculating the difference between the suspension tilt angle and the target leveling angle of 0° once the system completes its leveling action.

2) The leveling rate is measured as follows: after activating the leveling control system, the time required for the suspension to level is recorded, and the ratio of this time to the leveling angle provides the leveling rate.

3) The calculation method of the root mean square of the leveling error is shown in Equation (11).

$$S = \sqrt{\frac{\left[(x_1-\bar{x})^2+(x_2-\bar{x})^2+\ldots+(x_n-\bar{x})^2\right]}{n}} \tag{11}$$

where, S is the root mean square error of the leveling angle, (°); n is the number of samples; $\bar{x}$ is the average error of the leveling angle, (°); x_1, x_2, …, x_n are the points of leveling angle error sampling, (°).

Before conducting a field dynamic test, it is necessary to measure the slope of the test site. Two points on the sloping farmland should be selected: one at the bottom and one at the top of the slope. First, a tape measure is used to determine the horizontal distance between these two points. Then, the vertical height difference between them is measured. Finally, the slope angle is calculated using the inverse tangent function, based on the trigonometric relationship.

The harvester had both longitudinal and lateral inclinations when working on sloping ground, so the upper and lower leveling mechanisms needed to be leveled simultaneously to ensure the smoothness of the fuselage. The fuselage tilt angle (i.e., the sum of the pitch and roll angle vectors) was used as an important evaluation criterion for the leveling performance of the chassis attitude adjustment device [16,31] and was calculated as shown in Equation (12).

$$\gamma_i = \sqrt{\alpha_i^2+\beta_i^2} \tag{12}$$

where, α_i and β_i are the longitudinal and lateral attitude angles at a given moment, (°); γ_i is the tilt angle of the fuselage at a given moment, (°).

3 Results and discussion

3.1 Static leveling test

The upper suspension started to stabilize at 3.86 s and leveled out at 5.96 s with a leveling error of 0.23°, as shown in Figure 12 for the side-slope forward stance. The upper suspension took 5.87 s to level and 3.95 s to stabilize during side-slope back stance, with a leveling error of 0.24°. In the uphill stance, the lower suspension of the device began to stabilize at 2.89 s and was adjusted to the horizontal at 4.23 s, and the leveling error was 0.31°. In the downhill stance, the lower suspension started to stabilize at 4.16 s and was adjusted to the horizontal at 5.58 s with a leveling error of 0.34°. No oscillations occurred during the static leveling tests.

Five static leveling tests were completed for each of the four attitudes of the device, the leveling error and leveling rate in the tests were recorded, and the average error and root mean square of the error were obtained, as listed in Table 3. The maximum error in suspension leveling for the four attitudes was 0.37°, the fastest leveling rate was 0.233 s/(°), the average adjustment rate was 0.306 s/(°), the average leveling error was 0.28°, and the maximum root mean square error was 0.024°.

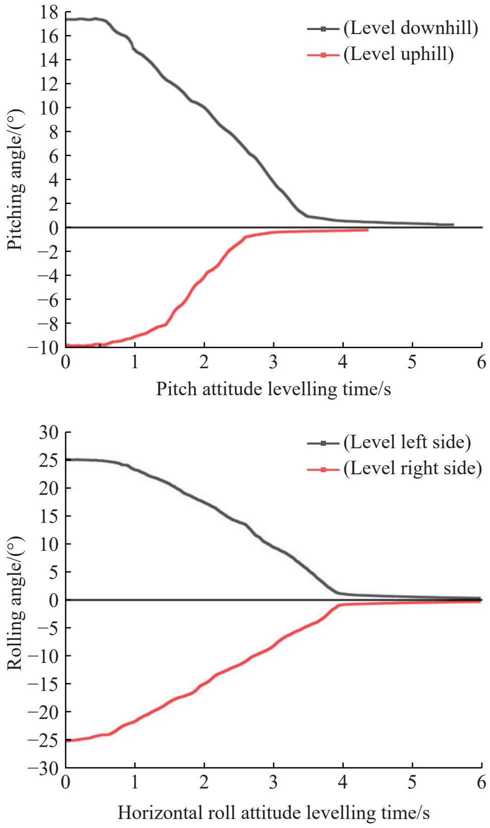


Figure 12 Results of static leveling test

Table 3 Comparison of model prediction results

Starting angle of suspension/(°)	Leveling angle error/(°)	Leveling rate /s·(°)⁻¹	Average error/(°)	Root mean square of error/(°)	Average of leveling rate /s·(°)⁻¹
	–0.24	0.235			
	–0.23	0.233			
–25	–0.21	0.236	–0.23	0.014	0.235
	–0.25	0.236			
	–0.22	0.234			
	0.23	0.238			
	0.21	0.235			
25	0.22	0.237	0.23	0.014	0.236
	0.24	0.234			
	0.25	0.236			
	–0.31	0.423			
	–0.34	0.429			
–10	–0.29	0.418	–0.32	0.017	0.424
	–0.32	0.424			
	–0.33	0.426			
	0.34	0.328			
	0.32	0.331			
17	0.37	0.323	0.33	0.024	0.327
	0.34	0.324			
	0.30	0.328			

The leveling error requirements for agricultural vehicles[32-33] were met by the average leveling rate of 0.306 s/(°) and the maximum leveling error of 0.37° observed in static tests at four limiting attitudes. The test results in Table 3 show that the small difference between the left and right leveling results was due to the structural lateral symmetry of the upper leveling mechanism. Error variance values for attitude leveling on uphill and downhill slopes varied. This was due to variations in the rotational momentum of the upper and lower connecting rods and the adjusting plate, as well as the expansion volume of the front and rear hydraulic cylinders, when the lower leveling mechanism was in operation.

3.2 Field test

The fuselage tilt angle was the same as the slope when the leveling process had not yet begun (shown as ① to ③ in Figure 13). The field conditions were complex and varied, and the fuselage tilt angle changed obviously during the time periods of 31.61-37.13 s, 72.51-78.29 s, and 91.54-95.04 s. The device leveled the fuselage in real time after starting the leveling procedure, and the attitude changes of the fuselage are shown as ④ to ⑥ in Figure 13. The fuselage tilt angle was leveled from the initial angle 12.88° to 0.52° and stabilized at 4.48 s when the harvester was running. For the three slope changes during the test, it took 4.10 s, 3.72 s, and 3.86 s to adjust the fuselage tilt angle from 5.59°, 5.14°, and 4.19° to 1.12°, 0.99°, and 0.91°, respectively. When the harvester was in motion, the maximum fuselage tilt angle was 1.81°, the minimum value was 0.13°, and the average fuselage tilt angle was 0.78°.

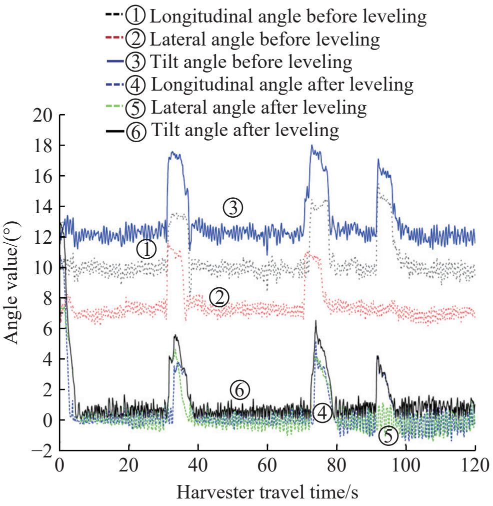


Figure 13 Comparison of field test results

Researchers have carried out single lateral or longitudinal leveling tests on the designed leveling device in the field, and the leveling system performed well, providing a reference for this study. However, the harvester is often operated in the field with both lateral and longitudinal angles. The results of the field tests in this study showed that the average fuselage tilt angle was 0.78°, which was within 1° and able to meet the needs of autumn maize harvesting operations[32]. The maximum fuselage tilt angle was 1.81°, and the minimum one was 0.13°. Tilt inclination of the fuselage had the phenomenon of error fluctuation, which was caused by the vibration of the engine, the removal fan, the straw returning cutter roller, and the unstable field conditions[34,35].

The crawler chassis attitude adjustment device can successfully adjust the attitude of the fuselage and accomplish the lateral and longitudinal adjustment of the fuselage, according to the results of the static and dynamic leveling tests. Most leveling solutions suggested by academics currently working make use of a single-layered leveling suspension when it comes to leveling angles[13-18]. With a tight installation and little room for rotation between the components, the adjustment of the longitudinal and lateral attitude of the fuselage depends on the movement of the connecting sections moved by hydraulic cylinders. The double-layered leveling frame structure used in this research allows for separate longitudinal and transverse leveling, reducing interference between leveling components and enabling a maximum longitudinal leveling angle of 17°, thereby expanding the range of slope operations. The center of gravity of the vehicle is continuously moved towards the side with the low potential when the harvester is operating on a side-slope, increasing the mass of the grain container and increasing the likelihood that it will roll over. The leveling structure of researchers depends on the lateral angle formed by the height differential caused by the hydraulic cylinder system lifting the height on one side but not the other[36,37]. The lateral hydraulic cylinders in this study do not interfere with each other and can achieve a greater lateral leveling angle of 41.3°, improving the safety of the harvester in side-slope operations.

4 Conclusions

In order to solve the problem of the tilting of the self-propelled maize harvester fuselage relative to the ground when it is working on a slope, a chassis attitude adjustment device has been developed. The device was made up of a double-layered leveling mechanism and a leveling control system, and it was used to regulate the lateral and longitudinal attitude of the harvester. The longitudinal and lateral tilt inclination of the fuselage were leveled by the upper and lower mechanisms, respectively. According to the vector method, the limit leveling angle of the upper mechanism was –43.1° to 43.1°, and the limit leveling angle of the lower mechanism was –10° to 17°. This study effectively improved harvester adaptability when working in a slope environment.

Static leveling tests and field tests were carried out to verify the leveling performance of the device. According to the findings of the static tests, the chassis attitude adjustment device can level the fuselage in four tilt attitudes: 10° uphill, 17° downhill, 25° sideways slope forward, and 25° sideways slope return, with a maximum leveling error of 0.37° and the fastest leveling rate of 0.233 s/(°). For the purpose of evaluating the chassis attitude adjustment performance of the device in the field tests, the tilt inclination of the fuselage was selected as an assessment indicator. The body tilt of the harvester ranged from 0.13° to 1.81° at a harvester speed of 2.5 km/h, with an average body tilt angle of 0.78°, showing that the undercarriage attitude adjustment system is capable of actively leveling the maize harvester attitude. This study can provide a useful reference for the design of slope travel devices for maize harvesters.

In the next stage of research, we will examine how different dynamic loads affect the posture adjustment of the harvester's body during slope operations, as well as the impact of varying forward speeds and slope conditions on the critical fuselage tipping angle. These studies aim to further enhance the slope performance of crawler maize harvesters.

Acknowledgements

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[References]

[1] Chen Z, Hao F P, Wang F D, Su W F, Cui J W. Development of technology and equipment of corn harvester in China. Transactions of the CSAM, 2012; 43(12): 44–50. (in Chinese)

[2] Lin J H, Yang M L, Zhang X J, Liu P W, Li S, Peng J. Evaluation of wheat and corn harvester selection in hilly and mountainous area. Transactions of the CSAM, 2022; 53(S1): 150–157. (in Chinese)

[3] Tang Z F, Liu S P, Zhou F J, Li T Y, Wang J L, Li C Y. Design and experiment of ear harvester for seed corn. Transactions of the CSAM, 2021; 52(7): 102–112. (in Chinese)

[4] Li Y F, Zang L G, Shi T, Lv T, Lin F. Design and dynamic simulation analysis of a wheel-track composite chassis based on RecurDyn. World Electr Veh J, 2022; 13(1): 12.

[5] Zemánek T, Neruda J. Impact on the operation of a forwarder with the wheeled, tracked-wheel or tracked chassis on the soil surface. Forests, 2021; 12: 336.

[6] Ahn T, Lee Y, Park K. Design of integrated autonomous driving control system that incorporates chassis controllers for improving path tracking performance and vehicle stability. Electronics, 2021; 10(2): 144.

[7] Du X Q, Ning C, Yang Z H, Ma C H, He L Y, Han X T. Design and experiment of hydraulic system for crawler chassis of straddle type camellia oleifera fruit harvester. Transactions of the CSAM, 2023; 54(3): 139–147. (in Chinese)

[8] Wei Z C, Wang X H, Li X Q, Wang F M, Li Z H, Jin C Q. Design and experiment of crawler self-propelled sorting type potato harvester. Transactions of the CSAM, 2023; 54(2): 95–106. (in Chinese)

[9] Hiregoudar S, Udhaykumar R, Ramapp.K T, Shreshta B, Meda V, Anantachar M. Artificial neural network for assessment of grain losses for paddy combine harvester a novel approach. In: Balasubramaniam P. (Ed. s). Control, Computation and Information Systems. Berlin, Heidelberg: Springer, 2011; pp.221–231.

[10] Wang Z Z, Yang J, Liu P Y, Long X J, Li H T, Wei W J. Development of an agricultural vehicle leveling system based on rapid active leveling. Biosystems Engineering, 2019; 186: 337–348.

[11] Zhu Y, Kan J M. Prediction of the lateral stability of a forestry chassis with an articulated body and fitted with luffing wheel-legs. Biosystems Engineering, 2022; 224(2): 143–160.

[12] Wang L L, Lan H, Zhou X, Chen D, He Z Z, Li Z. Design and experiment of active rollover control system using control moment gyroscope for agricultural wheeled tractor. Transactions of the CSAM, 2022; 53(S2): 320–327. (in Chinese)

[13] Geng D Y, Sun Y C, Li H B, Mu X D, Zhang G D, Wang Z Y, et al. Design and experiment of crawler corn harvester for sloping fields. Transactions of the CSAE, 2021; 37(13): 11–19. (in Chinese)

[14] Sun Y X, Xu L Z, Jing B, Chai X Y, Li Y M. Development of a four-point adjustable lifting crawler chassis and experiments in a combine harvester. Computers and Electronics in Agriculture, 2020; 173(2): 105416.

[15] Hu J P, Pan J H, Dai B W, Chai X Y, Sun Y X, Xu L Z. Development of an attitude adjustment crawler chassis for combine harvester and experiment of adaptive leveling system. Agronomy, 2022; 12(3): 717.

[16] Jin C Q, Yang T X, Liu G W, Wang T E, Chen M, Liu Z. Design and test of posture controlled chassis for caterpillar combine. Transactions of the CSAM, 2020; 51(11): 393–402. (in Chinese)

[17] Liu P Y, Ke C P, Ke T, Li H T, Wei W J, Zhao C. Design and experiment of pre-detection active leveling agricultural chassis for hilly area. Transactions of the CSAM, 2020; 51(3): 371–378. (in Chinese)

[18] Liu P Y, Peng F J, Li H T, Wang Z Z, Wei W J, Zhao J P. Design and experiment of adaptive leveling chassis for hilly area. Transactions of the CSAM, 2017; 48(12): 42–47. (in Chinese)

[19] Benjieming E R. Level control method for an agricultural combine. 2017; US10375890B2.

[20] Ryan P M, Ryan S H. Leveling by over-compensation. 2007; US2007123326A1.

[21] Toshinori K. Working machine. 2008; JP5313516B2.

[22] Haruji F, Akito N. Combine Harvester. 2009; JP5508619B2.

[23] Zhou Y J, Li S H, Xu Q, Zhang F K. Kinematic analysis and optimal design of 3-PUS-PU compliant parallel mechanism. Transactions of the CSAM, 2022; 53(9): 417–424. (in Chinese)

[24] Dong X, Wang P H, Liu L Y, Zuo Y J, Li Z H, Jia F G. Design and experiment of the cam driven bag opening mechanism for raw grain packing machine. Transactions of the CSAE, 2022; 38(15): 42–52. (in Chinese)

[25] Jing B. Research on the technology of multi-point lifting and lowering chassis about the tracked combine harvester. Master dissertation. Zhenjiang: Jiangsu University, 2019; 101p. (in Chinese)

[26] Law Press. Soil and water conservation law of the People's Republic of China. Beijing: Law Press, 2010; 7. (in Chinese)

[27] Shi X. Study on the leveling system of the body in a self-propelled corn combine harvester. Master dissertation. Changchun: Jilin University, 2017;

114 p. (in Chinese)

[28] Sun Y J, Zhou J, Li X Q, Sun Y T, Zhang Z Q, Chen G. Design and experiment of body leveling system for potato combine harvester. Transactions of the CSAM, 2020; 51(S1): 298–306. (in Chinese)

[29] Hu L, Lin C X, Luo X W, Yang W W, Xu Y, Zhou H, et al. Design and experiment on auto leveling control system of agricultural implements. Transactions of the CSAM, 2015; 31(8): 15–20. (in Chinese)

[30] Xu T B, Gao D J, Chen Y, Zhang W W, Xu F, Zhou P. Vibration response of the crawler combine chassis frame excited by the engine. International Journal of Rotating Machinery, 2021; 2021(1): 6675003.

[31] Shu X, Jiang P, Hu W W, Shi Y X, Lin W, Dong C Q. Design and test of the chassis leveling system for the high ground gap plant protection machine. Journal of Hunan Agricultural University, 2019; 45(3): 321–326. (in Chinese)

[32] Li S P, Yan Y X, Xu B, Li K H, Li W, Peng Z. Design and experiment on leveling control system of scissor type sugarcane transporter in hilly area. Transactions of the CSAM, 2021; 52(11): 384–393. (in Chinese)

[33] Peng H, Ma W X, Zhao E P, Lu X Q, Feng X. Design and physical model experiment of body leveling system for roller tractor in hilly and mountainous region. Transactions of the CSAE, 2018; 34(14): 36–44. (in Chinese)

[34] Wang Z S. Research on body leveling system and leveling control of hily mountain tractor. PhD dissertation. Changchun: Jilin University, 2022; 149 p. (in Chinese)

[35] Ding H T, Chen S R, Zhou W W, Liang R Z. Mechanism analysis of combine harvester’s vibration characteristics under feeding interference. Transactions of the CSAM, 2022; 53(S2): 20–27, 51. (in Chinese)

[36] Sun J B, Chu G P, Pan G T, Meng C, Liu Z J, Yang F Z. Design and performance test of remote control omnidirectional leveling hillside crawler tractor. Transactions of the CSAM, 2021; 52(5): 358–369. (in Chinese)

[37] Zhang K X, Zhang L, Li Z P, Yin Y P, Liu X X, Zhao X Y. Design and test of twisting and swinging attitude adjustment device of wheel hilly tractor. Transactions of the CSAM, 2022; 53(6): 425–433. (in Chinese)