agriculture

MDPI

Article

Design and Testing of a Crawler Chassis for Brush-Roller Cotton Harvesters

Zhenlong Wang [1], Fanting Kong [1], Qing Xie [1], Yuanyuan Zhang [1], Yongfei Sun [1], Teng Wu [1] and Changlin Chen [2,*]

1 Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China; 82101225604@caas.cn (Z.W.); kongfanting@caas.cn (F.K.); xieqing@caas.cn (Q.X.); 82101222110@caas.cn (Y.Z.); sunyongfei@caas.cn (Y.S.); wuteng@caas.cn (T.W.)
2 Graduate School of Chinese Academy of Agricultural Sciences, Beijing 100083, China
* Correspondence: chenchanglin@caas.cn

Abstract: In China's Yangtze River and Yellow River basin cotton-growing regions, the complex terrain, scattered planting areas, and poor adaptability of the existing machinery have led to a mechanized cotton harvesting rate of less than 10%. To address this issue, we designed a crawler chassis for a brush-roller cotton harvester. It is specifically tailored to meet the 76 cm row spacing agronomic requirement. We also conducted a theoretical analysis of the power transmission system for the crawler chassis. Initially, we considered the terrain characteristics of China's inland cotton-growing regions and the current cotton agronomy practices. Based on these, we selected and designed the power system and chassis; then, a finite element static analysis was carried out on the chassis frame to ensure safety during operation; finally, field tests on the harvester's operability, stability, and speed were carried out. The results show that the inverted trapezoidal crawler walking device, combined with a hydraulic continuously variable transmission and rear-drive design, enhances the crawler's passability. The crawler parameters included a ground contact length of 1650 mm, a maximum ground clearance of 270 mm, a maximum operating speed of 6.1 km/h, and an actual turning radius of 2300 mm. The maximum deformation of the frame was 2.198 mm, the deformation of the walking chassis was 1.0716 mm, the maximum equivalent stress was 216.96 MPa, and the average equivalent stress of the entire frame was 5.6356 MPa, which complies with the physical properties of the selected material, Q235. The designed cotton harvester crawler chassis features stable straight-line and steering performance. The vehicle's speed can be adjusted based on the complexity of the terrain, with timely steering responses, minimal compaction on cotton, and reduced soil damage, meeting the requirements for mechanized harvesting in China's inland small plots.

Keywords: cotton; harvester; crawler; chassis; simulation; finite element analysis (FEA)

Citation: Wang, Z.; Kong, F.; Xie, Q.; Zhang, Y.; Sun, Y.; Wu, T.; Chen, C. Design and Testing of a Crawler Chassis for Brush-Roller Cotton Harvesters. *Agriculture* **2024**, *14*, 1832. https://doi.org/10.3390/agriculture14101832

Academic Editor: Simone Bergonzoli

Received: 4 September 2024
Revised: 14 October 2024
Accepted: 15 October 2024
Published: 17 October 2024

1. Introduction

Cotton is one of China's principal economic crops and plays a crucial role in national economic development. As a strategic and vital raw material in the textile industry [1,2], cotton is directly linked to national economic progress and the livelihood of farmers. As China's primary economic crop, cotton constitutes a major pillar of national economic development [3]. The main cotton-producing areas in China include the Yangtze River basin, the Yellow River basin, and the Xinjiang cotton region. In 2023, the total area planted with cotton was 4182.2 square kilometers, with a total production of 5.618 million tons, of which cotton production from the Yangtze and Yellow River basins accounted for 9% of the total.

Internationally, a comprehensive theoretical system for the basic design of a large-scale crawler chassis has been established, along with simulation optimization techniques and mature manufacturing processes. In recent years, to adapt to a broader range of operating environments, beneficial explorations have been made toward miniaturization and lightweight design of the crawler chassis. Given that cotton is predominantly cultivated on farms abroad, where the terrain is relatively flat and mostly suited to large harvesters, these machines are not suitable for use in the inland areas of our country. John Deere's Model 7760 cotton harvester, one of the most advanced in the world, features a continuously variable transmission system in its chassis, allowing for the automatic adjustment of the operating speed based on varying field conditions and cotton types. It is capable of simultaneously performing cotton picking, cleaning, and baling operations in the field. Case's most representative model, the ME625 cotton harvester, employs a lightweight design philosophy, reducing the machine's weight and enhancing its overall mobility and operability. It can move flexibly across various terrains, and its cutting platform is equipped with automated controls that adjust the machine's speed and cutting depth based on different cotton varieties and terrain conditions. China began its research on crawler chassis relatively late, but after decades of development, the research on large crawler chassis has become relatively well-established. Research on crawler chassis in China primarily focuses on theoretical analysis, structural optimization, and simulation analysis, particularly on large crawler chassis, with less emphasis on lightweight crawler chassis suited to China's specific terrains. With the advancement of hydraulic technology, chassis machinery that utilizes hydraulic systems offers advantages such as compact structures and convenient automatic control. Currently, domestic scholars mainly focus on research concerning driving methods, turning performance, and cross-country capability. Regarding the drive method, Han Mingxing [4] proposed a crawler chassis with a hybrid hydraulic–electric drive system, employing the following two independent drive modes: hydraulic and electric. By utilizing the closed-loop control of servo motor speed and force, the system can be adjusted based on changes in external chassis load, significantly improving the dynamic output characteristics of the closed hydraulic drive system. This approach enhances the overall dynamic control performance of the machine and reduces energy consumption during operation. Wu Tengfei [5] and others developed a crawler tractor for the hilly and mountainous areas of the southwest, utilizing a fully hydraulic continuously variable transmission. Utilizing microcontroller technology for remote control, subsequent tests on steering performance and turning radius demonstrated strong cross-country capability and stability on hilly mountain roads. Xu Gaowei [6] and others addressed the issue of existing electric chassis not meeting the diverse operational demands of orchards by designing a matching power system for orchard crawler chassis, operated via wireless remote control. The transmission employs an electric drive and a differential-less device, simplifying the transmission system.

The crawler chassis uses tracks as its walking components, which, compared to wheeled chassis, allow the vehicle to continuously provide strong traction across various terrains due to the rolling motion of the crawler. This design achieves better passability on uneven agricultural terrains and is capable of adapting to a variety of complex terrains, such as muddy, slippery, and uneven grounds, offering higher traction. This is particularly useful for operations requiring significant traction. The walking system of the power chassis must possess strong stability, obstacle negotiation, and flexibility [7]. For example, in tilling and harvesting, it enhances operational efficiency.

In China's Xinjiang cotton region, where large areas are cultivated primarily on plains with concentrated planting areas, advanced mechanized cotton harvesting technologies have been first implemented domestically. These technologies are relatively mature, achieving a mechanization rate of over 90%. The main issues currently in the Yangtze and Yellow River basins include the following: (1) the fragmented and dispersed nature of the cultivation areas, which complicates transitioning operations; (2) the complex terrain, significant slope, and irregular shape of the ground further increase the difficulty of operations; (3) the relatively humid climatic conditions of the cotton-growing areas in the Yangtze and Yellow River basins make it difficult for large harvesters from the Xinjiang region to access these sites, rendering them unsuitable for mechanized harvesting in small inland plots, resulting in a mechanization rate of less than 10% in these areas.

This paper focuses on the calculation and selection of key components, and the overall frame's structural design of a crawler chassis for brush-roller cotton harvesters. It requires the chassis to have high power and strong pass-through ability, while also meeting criteria such as low rolling rates, minimal crawler settlement, high ground clearance, and a small turning radius [8]. The selection of the chassis walking device for the brush-roller-crawler cotton harvester is optimized based on the characteristics of hydraulic transmission to enhance the efficiency of harvesting operations. Considering agronomic planting patterns, the design of the crawler walking chassis aims to reduce wear on the crawler during operation and decrease the crushing of cotton stalks. The safety of the cotton harvester's crawler chassis is verified through simulations using ANSYS Workbench 2022 R1 finite element software, followed by prototyping and field validation.

2. Materials and Methods

2.1. Overall Design Scheme

Considering the topography of the Yangtze and Yellow River basins in China, along with the agricultural requirements for brush-roller-type crawler cotton harvesters, this study focuses on the design of the drive method and the crawler chassis structure for brush-roller-type cotton harvesters.

1. Given the shortcomings in the mechanized harvesting of cotton in the Yangtze and Yellow River basins in China, combined with the agronomic requirements for cotton cultivation, the current standardized planting model typically has a plant spacing of 15 cm and a row spacing of 76 cm. The design for picking spans three rows, and the operational mode employs a pattern of skipping three rows and harvesting three rows, as shown in Figure 1.

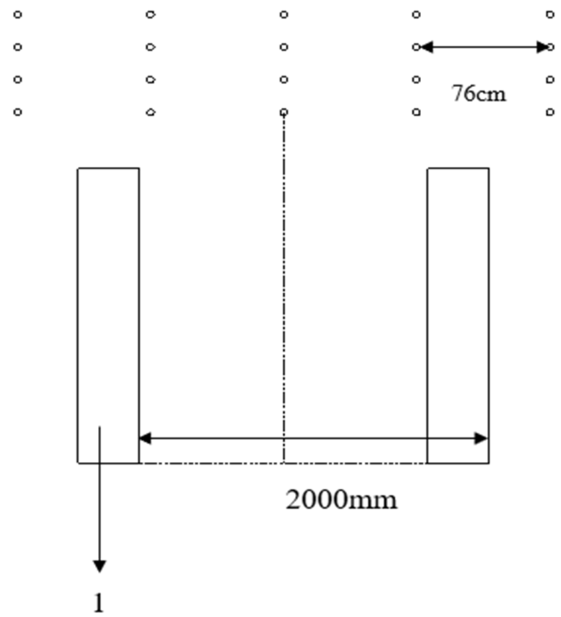


Figure 1. Schematic diagram of the operating mode of the brush-roller-type crawler cotton harvester: (1) crawler.

2. Based on the agronomic requirements for cotton cultivation and the harvesting operation mode, the track gauge of the crawler chassis was set at 2000 mm, with a ground contact length of 1650 mm. An inverted trapezoidal crawler was used as the locomotion device, and the maximum ground clearance of the chassis was 270 mm to accommodate the operational needs under varying terrain conditions.
3. Hydraulic technology was utilized to bypass the traditional mechanical power output, employing a continuously variable transmission as the power drive for the crawler

chassis, which enhances adaptability. Concurrently, a rear-wheel drive system was employed as the propulsion source, offering higher traction and greater adaptability.

2.2. Overall Structure and Working Principle

Overall structure: The machine is primarily composed of working parts, the main frame, moving parts, and a power system [9]. The brush-roller-crawler cotton harvester is divided into the following three sections: front, middle, and rear. The front section includes the working components such as the cutting platform, auger, and cotton boll collection apparatus; the middle section comprises the cab, the pneumatic transport channel, and components like the engine and fan; the rear section consists of the cotton basket and its fixed base.

The crawler chassis primarily consists of the chassis frame, track wheel system, engine, transmission, tracks, tensioning device, etc. [10], and is divided into the following three layers: upper, middle, and lower. The upper layer includes the fixed bases for the driver's cabin, fan, and cotton box. The middle section comprises hydraulic drive components (hydrostatic transmission system, HST), transmission, and engine mount, while the lower layer (walking parts) consists of the chassis frame, four-wheel drive system (drive wheel, guide wheel, load-bearing wheel, and crawler), and track guide, as shown in Figure 2.

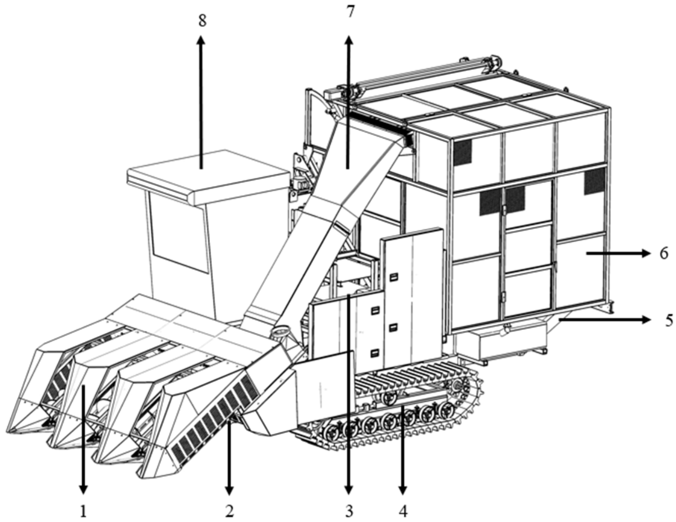


Figure 2. Brush-roller-crawler cotton harvester: (1) cutterhead assembly; (2) cotton boll collecting device; (3) blower; (4) propulsion chassis; (5) cotton bin base; (6) cotton bin; (7) air conveyance channel; (8) operator's platform.

The machine is equipped with the following three gear settings: high, medium, and low speed. The speeds are 6.1 km/h for high, 4.1 km/h for medium, and 2.0 km/h for low. By engaging different gears in the mechanical gearbox via the clutch, varying torques are transmitted, thereby facilitating the switching of speed requirements under different operating conditions of the machine.

Operating Principle of the Whole Machine: The brush-roller-type crawler cotton harvester can sequentially complete processes such as cotton picking, cotton boll separation, cleaning, pneumatic conveying, cotton collection, and unloading. During the cotton-picking process, high-speed rotation of the brush rollers in the front cutting platform and movement along the crop direction contact the cotton plants, brushing off the bolls. These are then conveyed via auger to the pneumatic conveyance inlet. At this point, because of their weight, the bolls drop into the collecting device below, achieving separation from the cotton, which is then rapidly transported to the rear cotton box by a powerful airflow. The pneumatic conveying and cotton collection process utilize the power of the airflow to transport the cotton into the box for secure storage and transport. Finally, in the unloading process, the cotton box can be inverted and the cotton within unloaded using a chain rake, completing the entire mechanized cotton harvesting process. The technical parameters of the whole machine are shown in Table 1.

Table 1. Overall technical specifications.

Parameter	Numerical Values
Overall dimensions (L × W × H) (m)	6.5 × 2.6 × 3.4
Total mass (t)	5.2
Matching power (kW)	88.3
Working width (rows)	3
Cotton box volume (m^3)	10
Operating speed (m/s)	0.9

2.3. Working Principle of the Crawler Chassis

Crawler chassis are widely used in agricultural production. Based on different drive types, such as mechanical, hydrostatic, and electric drives, hydrostatic–mechanical drive is a method that combines hydrostatic technology with mechanical drive axles. Compared to conventional mechanical transmissions, hydraulic drives can deliver higher torque [11–13].

The powertrain of the crawler chassis primarily consists of an engine, a hydrostatic transmission (HST), and a mechanical gearbox, which serve as the power output sources for the operation, movement, and other functions of the brush-roller-crawler cotton harvester. The crawler chassis integrates technologies such as transmission, locomotion, hydraulics, steering, braking, and electromechanical and hydraulic control [14]. Figure 3 shows a diagram of the hydraulic drive working principle.

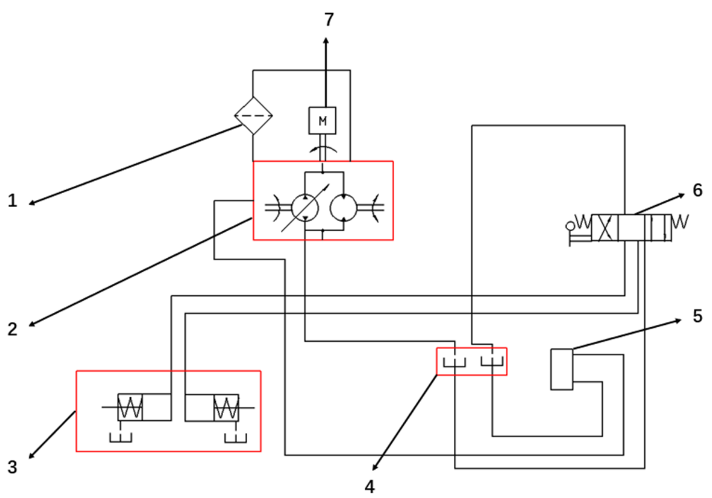


Figure 3. Hydraulic drive system of the crawler cotton harvester chassis: (1) oil filter; (2) HST (hydrostatic transmission); (3) steering cylinder; (4) oil tank; (5) fuel tank radiator; (6) three-position four-way valve; (7) engine.

Working Principle: The engine outputs power that directly drives the pulley to the HST input shaft (hydrostatic transmission hydraulic drive device). Within the HST, the hydraulic pump directly outputs high-pressure oil to the hydraulic motor, converting hydraulic energy into mechanical energy. Under the action of high-pressure oil, the hydraulic motor generates power, which is then transmitted to the mechanical gearbox through the output shaft. The mechanical gearbox adjusts and distributes power to meet various operational demands. Finally, power from the gearbox is transferred to the drive wheels located at either end of the drive axle, causing the crawler to move forward or backward. The principle of the traveling drive system is shown in Figure 4.

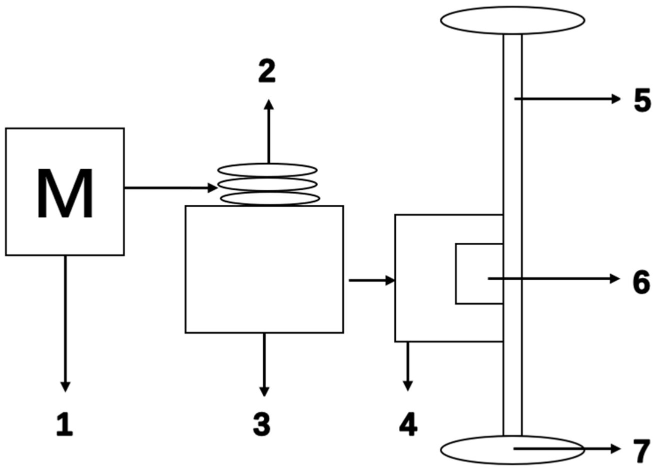


Figure 4. Schematic diagram of the walking drive system: (1) engine; (2) pulley; (3) HST (hydrostatic transmission); (4) mechanical gearbox; (5) drive axle; (6) steering cylinder; (7) Drive wheel. Annotation: In the figure, "M" means engine.

Steering State: The engine drives the hydraulic pump to output high-pressure oil to the control valve assembly. Through the control lever, the directional valve within the assembly is activated, which directs oil to the steering cylinder at the front of the transmission. This engages or disengages the shift paddles within the transmission. When turning left, the engine drives the hydraulic pump to extract hydraulic oil to the control valve assembly. The movement of the piston within the assembly alters the flow direction of the hydraulic oil, controlling the inlet of the steering cylinder. The oil is then directed to the left side of the steering cylinder, disengaging the paddle on the left side of the mechanical transmission, thereby halting the left crawler's operation. At this point, only the right crawler remains operational, enabling the vehicle to turn or rotate in place.

2.4. Calculation of Key Components of the Crawler Chassis

2.4.1. Calculation of Crawler Parameters

The crawler chassis has several advantages, including a large ground contact area, low ground pressure, continuous distribution of the average soil pressure, strong terrain adaptability, and high traction. It is currently the most widely used form in hilly areas [15,16]. The chassis is a key structure influencing the mobility of vehicles [17]. One of the primary reasons for using rubber tracks instead of tires in agricultural machinery is to reduce soil compaction [18]. To prevent further soil damage, the crawler chassis of the brush-roller cotton harvester utilizes rubber tracks. Additionally, considering that this design is intended for a cotton harvester's crawler chassis in the Yangtze and Yellow River basins of China, and based on the aforementioned terrain mobility requirements, an inverted trapezoidal rubber crawler chassis was selected for the brush-roller cotton harvester to enhance maneuverability. The structural parameters of the crawler primarily include the width of a single-side crawler, the crawler -ground contact length, and the number of crawler links [19].

The empirical formula for calculating the crawler's ground contact length is as follows:

$$\frac{L_1}{B} = 1.15 - 1.39 \tag{1}$$

In the formula, L_1 represents the length of the crawler contact area, measured in millimeters (mm).

The empirical formula for calculating the crawler width is as follows:

$$\frac{b}{L_1} = 0.18 - 0.24 \tag{2}$$

In the formula, b is the crawler ground contact length, measured in millimeters (mm). The empirical formula for calculating the crawler pitch is as follows:

$$P = (15 \sim 17.5)\sqrt[4]{G} \tag{3}$$

In the formula, P represents the crawler pitch, measured in millimeters (mm).

Considering the reduction in damage to cotton plants during field operation and integrating the scientific planting row spacing of cotton, along with the operation mode for harvesting three rows by crossing three, the design parameters were incorporated into Equations (1)–(3). This determined the crawler gauge of the crawler chassis to be 2000 mm, the ground contact length of the crawler to be 1650 mm, the crawler width to be 350 mm, and the crawler to consist of 54 sections.

2.4.2. Ground Contact Pressure

The ground pressure of the tracks of a crawler cotton harvester refers to the pressure per unit area when the crawler contacts the ground. Ground pressure is crucial for the design and selection of crawler. Excessive ground pressure can lead to ground depression or damage, while insufficient ground pressure may reduce friction with the ground, potentially affecting the traction and stability of the crawler. The calculation of the ground pressure can be determined as follows:

$$p_a = \frac{G}{2bL_1} = 45.02 \tag{4}$$

In the formula, p_a represents the average contact pressure of the crawler, KP_a; G denotes the resultant force composed of the machine's working weight and the vertical external load; b represents the width of the crawler contact area; and L_1 signifies the length of the crawler contact segment.

The crawler incline angle refers to the angle of inclination of the vehicle's front and rear ends relative to the horizontal plane, which affects the vehicle's stability, passability, and operational efficiency. An appropriate incline angle can enhance the passability of crawler vehicles, making it easier for them to navigate obstacles or uneven terrain. Considering the vehicle's obstacle-crossing capability and the stability to adapt to various road conditions, this paper adopts an inverted trapezoidal crawler design. The crawler incline angle (at the tension wheel) is set at 35°, while the rear incline angle (at the drive wheel) is 45°. To ensure the stability of the entire machine when operating on different surfaces, a low center of gravity is maintained, with a ground clearance of 260 mm. The main technical parameters of the overall chassis are presented in Table 2.

Table 2. Chassis parameters of the crawler-type cotton harvester.

Parameter	Numerical Values
Track width (mm)	350
Track ground contact length (mm)	1650
Track pitch (mm)	90
Wheelbase (mm)	2000
Transmission method	HST hydraulic continuously variable transmission
Steering method	Hydraulic power-assisted steering

2.5. Calculation of Chassis Power System

2.5.1. Engine Selection

As the power source of the vehicle, the engine provides power output for the vehicle's operation and movement, responsible for generating power to ensure steady operation of the machinery and to drive the vehicle forward and backward under various working conditions. Initially, the required power for the machine is considered to determine the range of power needed (including continuous and peak output power), typically reserving 10–20% of surplus power to ensure the engine can stably deliver the required output. The total power consumption of the machine primarily includes the power consumed by the engine itself, resistance during operation, power transmission losses, and power consumed by other auxiliary equipment. This paper will select the engine based on the maximum required power.

When the vehicle is in motion, it primarily encounters rolling resistance, slope resistance, and air resistance power consumption. This paper disregards the effects of air resistance.

(1) Calculation of Rolling Resistance:

$$F_r = m \cdot g \cdot f \tag{5}$$

In the formula, m is the total mass of the machine, taken as 5200 kg; g is the acceleration due to gravity, taken as 9.8 m/s^2; and f is the coefficient of rolling resistance, typically ranging from 0.08 to 0.12, with this study using the maximum value of 0.12.

(2) Calculation of Ramp Travel Resistance:

$$F_s = m \cdot g \cdot sina \tag{6}$$

In the formula, α is the slope angle, taken as 22°.

(3) Calculation of Total Traction Force:

$$F_t = F_r + F_S = 25.4 \tag{7}$$

In the formula, F_t is the total traction force, KN; F_r is the rolling resistance; and F_S is the ramp travel resistance.

(4) Calculation of Traction Power:

$$P = F_t \times V = 43.18 \tag{8}$$

In the formula, P is the traction power, KW; V is the maximum travel speed, taken as 1.7 m/s.

Upon substituting the data into Equations (5)–(8), the maximum traction force was calculated as 25.4 kN, with a required traction power of 48.18 kW. The machine is divided into three hydraulic system circuits, including the travel hydraulic system, the header working and lifting hydraulic system, and the cotton-box-lifting hydraulic system. The power required for the working components was calculated as 2.67 kW, and the total traction power required was 45.85 kW. Additionally, the power consumption in the hydraulic transmission is not negligible. To ensure power output during operation and to typically reserve 10–20% of the engine's power, the required rated power of the engine P should satisfy $P \geq F_t$. The Shandong Yunnei YN35CAF4 (Shandong Yunnei Power Co., Ltd., Weifang, China) diesel engine was chosen, with a power of 88.3 kW, a standard rotational speed of 2400 rpm, and a maximum torque of 422 N.m.

2.5.2. Hydraulic System Calculation

The chassis drive mechanism primarily comprises an HST, a mechanical transmission, and a drive shaft, utilizing a power transmission configuration in which the mechanical gearbox and HST are connected in series [20]. According to the circuit configuration, it can be divided into the following two major categories: open and closed circuits. The HST hydrostatic continuously variable transmission device mainly consists of a plunger pump, a manually controlled fixed-displacement motor, a make-up oil pump, an oil filter, etc., forming a closed-loop system.

Working Principle: Initially, the engine drives the plunger pump in the HST, converting mechanical energy into hydraulic energy through the reciprocating motion of the plunger pump, thus providing torque to the actuator. The plunger motor outputs driving force, facilitating the machine's forward and reverse movement and braking functionality. The make-up oil pump is used to replenish oil leaked from the system, ensuring its stable operation. The HST primarily consists of hydraulic pumps and motors, and the hydraulic motors selected for the power chassis must meet the requirements for maximum torque and maximum travel speed under various working conditions. In matching calculations, the selection of the hydraulic motor is completed first [21,22].

Calculation of the Walking Hydraulic System:

(1) Calculation of Hydraulic Motor Flow:

$$q_M = \frac{v_g \cdot n \cdot \eta_v}{1000} \tag{9}$$

In the formula, v_g is the displacement per revolution; n is the speed, in rpm, taken as 3000 rpm; and η_v is the volumetric efficiency, taken as 0.95.

(2) Calculation of Hydraulic Motor Torque:

$$T_M = \frac{\Delta P \cdot V_g}{2 \cdot \pi} \tag{10}$$

In the formula, η_{mh} is the mechanical hydraulic efficiency, taken as 0.94; ΔP is the pressure difference, taken as 38 MPa.

(3) Calculation of Power:

$$P_M = \frac{2\pi \cdot T \cdot n}{60{,}000} = \frac{q_v \cdot \Delta P}{600 \cdot \eta_t} = \frac{T \cdot n}{9549} \tag{11}$$

In the formula, η_t is the overall efficiency, taken as 0.9.

Upon substituting the design parameters into Equations (9)–(11), the required flow rate for the hydraulic motor was calculated as 150 L/min, with a torque of 302.5 N·m and a required power of 94.985 kW. Based on these calculations, the Zhejiang Aovite WHPM52 series hydrostatic transmission (HST) (Zhejiang Aovite Hydraulic Machinery Co, Ltd. Taizhou, China.) was selected, featuring a pump displacement of 52 mL/r, motor displacement of 52 mL/r, maximum flow of 156 L/min, maximum pressure of 40 MPa, maximum torque of 330.7 N.m, and maximum power of 103.9 kW.

2.5.3. Transmission Selection

The gearbox in crawler vehicles is a crucial component of the transmission system, responsible for adjusting and controlling the vehicle's speed, steering, and power transmission, directly affecting the vehicle's operational travel speed and steering stability. The drive axle of crawler vehicles is a complex transmission system, which works in coordination with the power unit, steering clutch, final drive, and rear axle casing, among other components. It reduces and redirects the power transmitted from the gearbox to the drive wheels to propel the vehicle and also facilitates steering. The design and integration of these components are crucial for the driving performance and stability of crawler vehicles, necessitating careful consideration of the machine speed when selecting the gearbox transmission ratio for crawler operation. Based on the above operational travel speeds, the transmission ratios were calculated for each gear of the walking gearbox [23], using the following formula:

$$i = \frac{60 \times 10^{-6} \pi n D}{v} \tag{12}$$

In the formula, i is the transmission ratio; n is the engine speed, taken as 2400 r/min; D is the pitch circle diameter of the crawler drive wheel, taken as 200 mm; and v is the gear speed, taken as 2 km/h.

Upon substituting the parameters into Equation (12), the transmission ratios were calculated as follows: first gear at 44.94, second gear at 22.1, and third gear at 14.81. The Linhai Baotian BT-21 (Linhai Baotian Agricultural Machinery Co, Ltd., Linhai, China.) model gearbox was selected.

2.5.4. Hydraulic Steering Device

The steering system of a crawler chassis typically consists of hydraulic power steering and mechanical control steering. This harvester features hydraulic steering and continuously variable transmission, with 360° on-the-spot turning [24]. Hydraulic steering operates by controlling the working state of the crawler on either side via hydraulic cylinders, facilitating the entire vehicle's steering, whereas mechanical steering is achieved through mechanical components such as connecting rods and steering rods. Hydraulic steering is characterized by its flexibility, quick response, and strong load adaptability. The steering mechanism of a crawler agricultural power chassis determines the overall maneuverability of the power chassis [25], typically featuring on-the-spot turning and unilateral braking steering. This paper employs hydraulic power steering, with the steering cylinder assembly installed as shown in Figure 5.

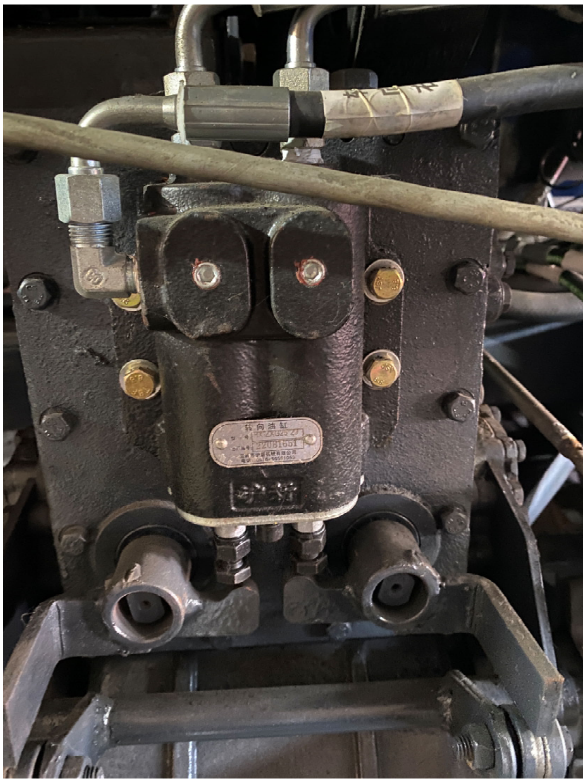


Figure 5. Steering cylinder.

The working principle is the same as that described in Section 2.2 for the crawler chassis. Under ideal conditions, the turning radius of the crawler cotton harvester was 2000 mm [26], as shown in Figure 6. The theoretical steering radius can be calculated using Equation (13). During actual steering, slippage of the crawler on the road surface cannot be ruled out; the actual measured steering radius is 2300 mm, as shown in Figure 7.

$$R = \frac{L(v_1 + v_2)}{2(v_1 - v_2)} \tag{13}$$

In the formula, L is the chassis wheelbase; v_1 is the linear velocity of the left crawler, in m/s; v_2 is the linear velocity of the right crawler, in m/s.

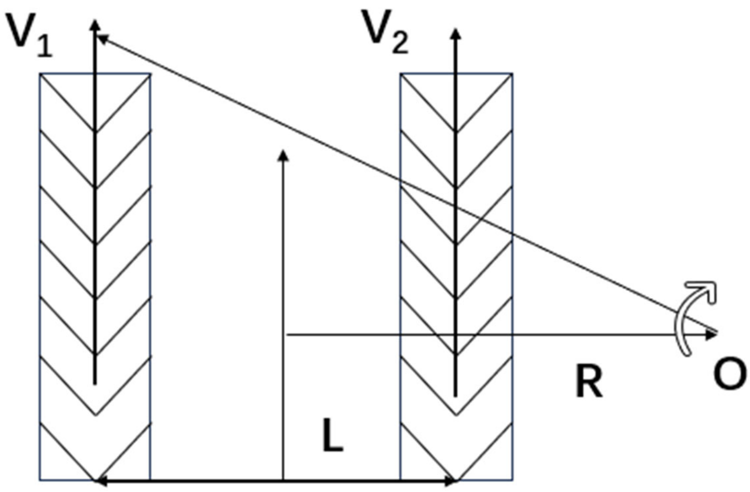


Figure 6. Schematic diagram of the turning process.

Figure 7. Turning in place.

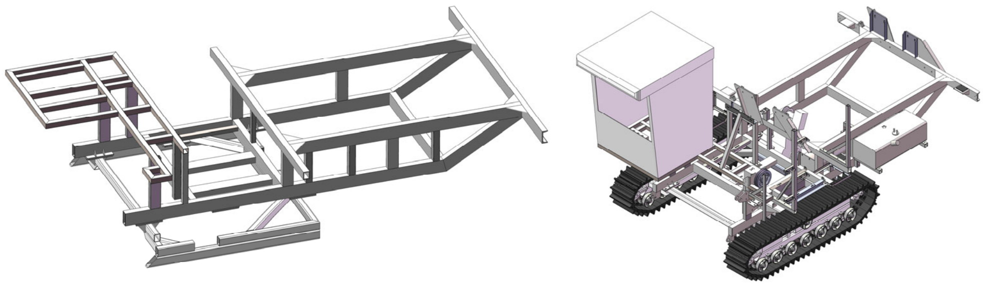
2.6. Chassis Structural Design

The frame of the brush-roller-type crawler cotton harvester is a crucial component of the entire vehicle, as it supports the weight of the vehicle's parts and cargo and is subjected to external forces. It plays a vital role in ensuring the structural stability, overall rigidity, and the rational design of the frame. The walking chassis of the brush-roller-type crawler cotton harvester mainly consists of four wheels and a belt (i.e., guide wheels, load-bearing wheels, carrier wheels, driving wheels, and tracks), auxiliary guiding devices, and auxiliary guiding devices. The finite element model of the chassis frame is primarily divided into upper and lower frame sections [27].

1. Load-Bearing Capacity: The reliability of the frame is a critical basis for assessing the safe operation and driving performance of the vehicle. The frame primarily provides fixed support for the cabin, cotton box, power system, and cotton box. The mass of each component is as shown in Table 3, and they ensure it can withstand the expected weight of the components and dynamic loads. The spatial mass layout is $4273 \times 2400 \times 360$ mm^3.
2. Material Selection: The chosen materials for the walking chassis frame should exhibit sufficient strength, rigidity, and corrosion resistance. The brush-roller-type crawler chassis frame was welded using Q235 carbon structural steel. To explore the frame's safety for the entire machine, a static structural analysis was conducted using ANSYS Workbench 2022 R1 to ensure the chassis frame meets the required strength and rigidity, as shown in Figure 8a.
3. Spatial Layout: The layout facilitates the installation and maintenance of various parts of the vehicle, such as the transmission walking system, transmission working system, and other components, ensuring a rational and compact vehicle structure, as shown in Figure 8b.

Table 3. Mass of each chassis structure.

Name	Parameter
Total machine weight (N)	50,960
Chassis weight (N)	21,560
Cabin (N)	1960
Header (N)	10,810
Cotton box (N)	5101.2
Engine (N)	4120.2
Transmission (N)	1765.8



(**a**) (**b**)

Figure 8. Overall diagram of the walking chassis: (**a**) chassis frame; (**b**) crawler-type walking chassis.

In conclusion, the brush-roller-type crawler cotton harvester combines the engine, hydrostatic system (HST), mechanical gearbox, and steering cylinders to operate in coordination. The power output from these components provides the vehicle with its power source for operations, continuously variable transmission, driving gear adjustment, and steering control, ensuring a stable power output and the flexible operation under various conditions, thereby ensuring operational efficiency in different scenarios. As illustrated in Figure 9, the overall assembly of the chassis transmission is shown.

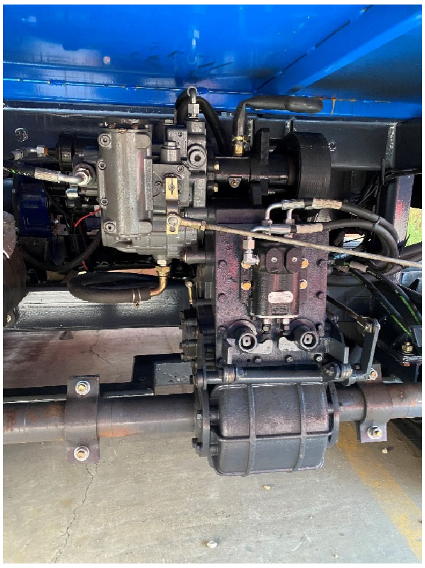


Figure 9. Overall assembly of the chassis transmission.

3. Finite Element Analysis of the Chassis

The chassis of a crawler cotton harvester is a critical component of the entire vehicle, serving as the key supporting structure that bears the weight of various parts and cargo while withstanding external forces. Ensuring the stability and overall rigidity of the chassis structure is essential for the machine's operation. The static structural simulation analysis of the harvester's chassis was conducted using ANSYS Workbench software to simulate and analyze parameters such as stress, strain, and displacement under static loading conditions. This analysis helps identify areas of stress concentration, allowing for the early detection of potential weak points in the structure and determining the stress distribution across different sections of the chassis. Moreover, the overall stiffness of the chassis is crucial; insufficient rigidity can lead to excessive deformation when carrying heavy loads or subjected to external forces. By conducting a simulation analysis, targeted reinforcement measures can be implemented to address structural weak points, preventing damage during actual operation and providing valuable insights for structural design optimization.

3.1. Preprocessing of Chassis Model

This paper initially used SolidWorks to create a comprehensive three-dimensional model of the frame. Given the complex actual structure of this harvester's chassis frame, the frame of the brush-roller-type crawler cotton harvester was simplified to enhance the simulation's accuracy [28]. In summary, the frame is a crucial load-bearing structure of the vehicle, and the performance of its chosen material directly affects the vehicle's safety and reliability during operation. To verify the reliability of the crawler chassis frame's strength, the entire frame chassis of the brush-roller-type crawler cotton harvester was welded using Q235 carbon structural steel. The material properties are as follows: density of 7.85 g/cm^3, elastic modulus of 210 GPa, Poisson's ratio of 0.3, yield strength of 235 MPa, and tensile strength of 370–500 MPa. A hexahedral mesh division [29] was used, resulting in 2,416,871 nodes and 389,991 elements.

The setting of loads and boundary conditions is critical to the accuracy of the finite element analysis results. For the chassis frame, boundary conditions are established, including fixed supports and applied loads on the structure, to simulate the actual working conditions and loading scenarios. Based on the mass of the various structures in the chassis listed in Table 3, loads and boundary conditions were applied to the frame. The main load-bearing components of the frame were subjected to uniformly distributed loads. In the figure, G represents the fixed constraint of the chassis frame. In this analysis, the weight of the hydraulic components (such as the hydraulic pump, hydraulic motor, hydraulic pipes, and hydraulic tank) was disregarded. The loading and boundary conditions for each part of the chassis frame are illustrated in Figure 10.

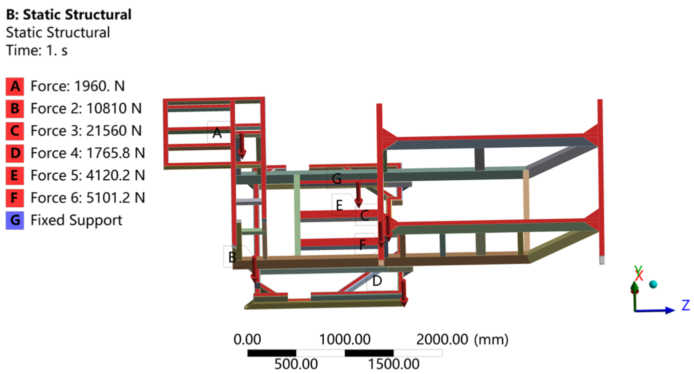


Figure 10. Force diagram of the chassis frame.

3.2. Results Analysis

(1) Stress Distribution

Utilizing the post-processing capabilities of ANSYS Workbench, the stress distribution cloud diagram of the entire frame can be viewed. Structural simulation analysis reveals that the maximum equivalent stress on the chassis frame is 216.96 MPa. The overall stress distribution, as shown in Figure 11, primarily indicates a minor stress concentration at the connection between the upper frame and the chassis, and potential conflicts caused by mesh division cannot be ruled out. Combined with the physical properties of the material, which are below the selected material's yield limit (235 MPa), the overall average equivalent stress of the frame is 5.6356 MPa. The results indicate that the chassis frame remains in an elastic state under the given load, without plastic deformation occurring. Simulation data and material properties confirm that the chassis frame meets safety requirements for use.

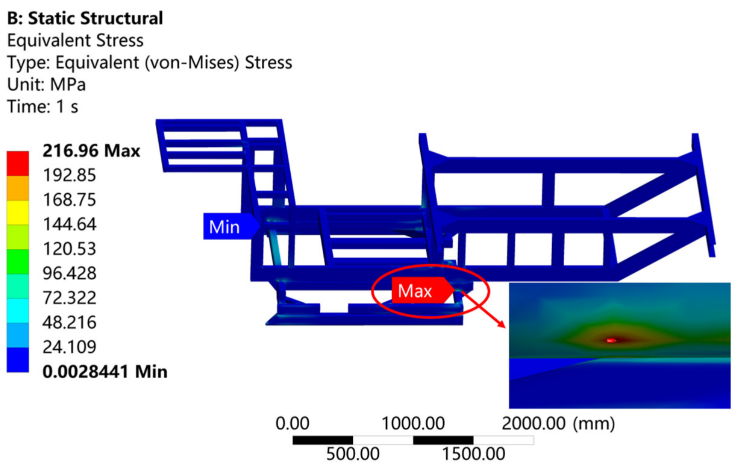


Figure 11. Equivalent stress deformation contour map.

(2) Deformation Conditions

According to the deformation cloud diagram, the maximum deformation occurs at the rear cross beam of the cotton box base. The diagram clearly shows localized stress concentration, likely due to the significant distance from the free end to the fixed constraints. The frame's maximum deformation is 2.198 mm, primarily because the right rear suspension's degrees of freedom are fully constrained and rigidly welded to the rear cross beam. This connection impedes torsional stiffness in this area, leading to stress concentration during frame torsion [30], as shown in Figure 12. The maximum deformation of the crawler walking chassis is 1.0716 mm, with no significant stress concentration observed in other areas of the overall frame. The deformation levels meet the design requirements.

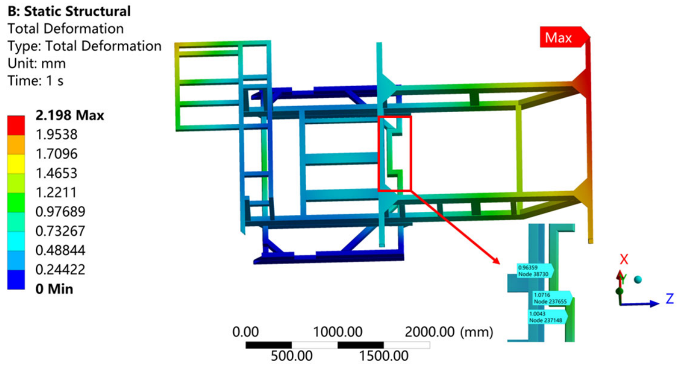


Figure 12. Total deformation contour map of the frame.

(3) Safety Factor

Based on the yield strength of the material and the calculated maximum stress value, the safety factor of the chassis frame can be determined. The safety factor is a crucial indicator for evaluating the structural safety, and it is generally required to be greater than a certain value. For Q235 material under static load conditions, where the load remains relatively stable, the risk of material failure is relatively low, and a safety factor in the range of 1.2 to 1.5 is acceptable. However, under dynamic load conditions, especially during field operations, the dynamic load on the crawler chassis becomes highly unpredictable. When crossing ditches or cutting obstacles, the chassis may experience impacts of uncertain magnitude. Additionally, the continuous vibration caused by working components during operation can also affect the chassis. In such cases, the safety factor is set between 2 and 3. In this paper, a safety factor of 3 was chosen to ensure that the structure remains intact during operation. According to this safety factor, the chassis frame meets the required safety standards for use, as shown in Figure 13.

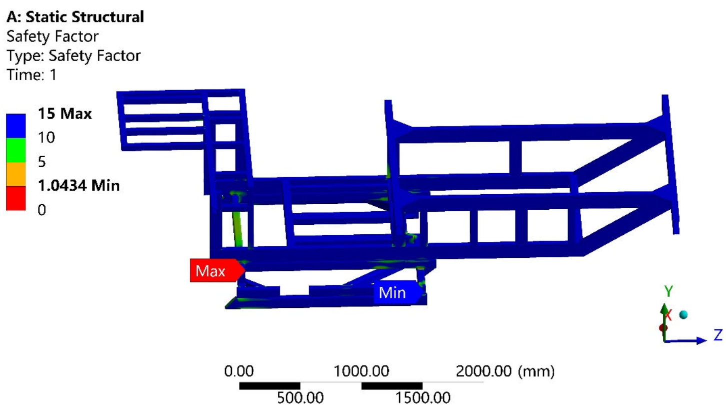


Figure 13. Safety factor contour map.

4. Results and Discussion

4.1. Field Trials

In summary, the power transmission of the brush-roller-type crawler cotton harvester was calculated and selected, and the overall frame was designed and validated through a simulation. The harvester is now being manufactured and field tested at cotton planting experimental fields in Nangong City and Tangshan City, Hebei Province, located in the inland cotton planting area of the Yellow River basin. The planting areas use a standardized row spacing of 76 cm. The testing sites are illustrated in Figure 14. Evaluations of the operational effectiveness in different regions are being conducted, examining the objectives mentioned above and verifying the machine's impact on crushing cotton plants. The field environmental parameters were measured in accordance with GB/T 5262 [31].

Figure 14. Field site of the experiment.

4.2. Purpose of the Experiment

To verify the actual operational effectiveness and overall performance of the brush-roller-type crawler cotton harvester, field tests are conducted. The main objectives of these field trials were the evaluation of the harvester under the following three conditions in a real-world operational environment, providing a basis for subsequent optimization:

(1) Chassis performance evaluation: Testing of the stability, reliability, and operational walking speed of the crawler cotton harvester in field conditions, as well as performance testing under various terrain conditions.

(2) Maneuverability testing: Assessment of the machine's control and flexibility during field operations, including steering in the field, making on-the-spot turns, and the impact of field surfaces on the crawler chassis components.

(3) Impact assessment: Examination of the machine's impact on cotton plant stubble during operations and an evaluation of its effects on the soil.

4.3. Chassis Performance Evaluation Test

4.3.1. Working Travel Speed

In summary, the harvester is equipped with the following three speed gears: high, medium, and low. The walking speed is determined by the position of the gear shift lever [32], with speeds of 2 km/h for low, 4.1 km/h for medium, and 6.1 km/h for high. To accurately understand the harvester's actual walking performance, straight-line speed tests were conducted during field harvesting, as shown in Table 4. The data indicate that the harvester's operational walking speed under the same terrain conditions meets the actual harvesting requirements. Additionally, on complex terrain during transition operations, speeds can be adjusted based on the actual conditions to enhance operational efficiency, save time and labor costs, and ensure the stability and safety of operations.

To further determine the actual operating speed of the cotton harvester, an analysis of its performance at various speeds was conducted to identify the optimal range of working speeds. Speed testing of the cotton harvester revealed a slight discrepancy between the actual operating speed and the theoretical driving speed. During actual operation, because of unavoidable errors in human operation, the relatively flat terrain of the planting areas, and efforts to enhance operational efficiency during harvesting, the actual speed of the machine is slightly higher than the theoretical speed. The results of the field tests are shown in Figure 15.

Table 4. Working speed test data.

Gear	Travel Distance/m	Travel Time/s	Average Time/s	Actual Speed (km·h^{-1})
First gear	100	129 93 120	114	3.168
Second gear		75.6 70.8 72	72.6	4.968
Three gears		61.2 34.8 60.6	63.6	6.876

(**a**) (**b**)

Figure 15. Field operation effect test: (**a**) field harvesting operation test; (**b**) effect of field harvesting test.

4.3.2. Maneuverability Test

The turning performance of the vehicle chassis is indicated by the turning radius, measured in accordance with GBT3871.5 [33]. The measured minimum turning radius was 2306 mm, which is slightly larger than the theoretical radius (2000 mm). This is due to the high overall weight of the machine and the predominance of soft soil in fields, which impacts the traction of the tracks. In summary, the entire machine's on-the-spot turning radius on a cement surface was measured at 2300 mm, as shown in Figure 5 above. Slippage of the tracks during turning cannot be ruled out, as illustrated in Figure 16a.

(**a**) (**b**)

Figure 16. Maneuverability test: (**a**) field turnaround test; (**b**) transition operation.

The on-the-spot turning capability for transition operations is an important demonstration of the flexibility of the brush-roller-type crawler cotton harvester. Test results show that during transition operations, the machine can complete an on-the-spot turn in a short amount of time, reducing the transition time and increasing the operational efficiency. Additionally, the brush-roller-type crawler cotton harvester was agile in field steering, able to quickly adjust direction to meet various operational needs, as shown in Figure 16b.

4.3.3. Impact Experiment

Based on the requirements for the operational mode of the brush-roller-type crawler cotton harvester, field test results indicate that the amount of cotton plant stubble during the harvesting process is minimal, as shown in Figure 17a. This meets agronomic requirements for harvesting without significantly affecting cotton growth and yield. The level of stubble is appropriate for agricultural planting requirements, minimizing the impact on cotton growth and ensuring that cotton plants maintain a good growth posture after harvesting. Additionally, the operation involves inverted trapezoidal rubber tracks which have a relatively large contact area with the ground, effectively dispersing the machine's weight and thereby reducing soil compaction. This results in minimal impact on the soil during operations, without causing severe soil compaction or damage, as illustrated in Figure 17b.

(**a**) (**b**)

Figure 17. Field operation effect test: (**a**) passability test; (**b**) crawler operation travel effect.

4.4. Discussion

Currently, in the Yangtze and Yellow River basins and inland small cotton-growing areas in China, the harvest of cotton is still predominantly manual due to topographical factors and the scales of the planting areas, which significantly slows down the progress of agricultural mechanization. This article proposes a crawler chassis suitable for a brush-roller-type cotton harvester. The harvester, as a whole, employs a lightweight design approach, effectively reducing the machine's weight and energy consumption compared to large cotton harvesters. Additionally, compared to other crawler chassis designs, the crawler chassis of this brush-roller-type cotton harvester is highly targeted and suitable, designed specifically for the needs of cotton planting and harvesting. It adapts better to the terrain and agronomic requirements of cotton growth, enhancing operational flexibility and ease of transfer. It is particularly suitable for actual application scenarios of mechanized harvesting of small plots of cotton in China's inland areas, where small-plot cotton planting poses greater challenges for agricultural machinery. However, this may also lead to relatively low versatility, making it difficult to apply to the harvesting of other crops or operations in other fields.

Based on field tests of the harvester, the quality of cotton picking is influenced by factors such as the growth condition and moisture content of the cotton plants. On the other hand, operating at too high a speed significantly affects the machine's travel speed.

While faster speeds cover more area per unit of time, thus increasing the efficiency of cotton picking, it may lead to clogging of the cutting platform. Therefore, it is necessary to adjust the travel speed according to the specific conditions of the cotton field.

Proposed future research on the chassis of the brush-roller-type crawler cotton harvester includes focusing on the vibration of the entire machine's frame and chassis, as this vibration significantly affects the performance and reliability of the harvester. Another consideration is the need for the machine to handle transition operations and the uncertain field terrain. Good passability ensures that the harvester can overcome various obstacles smoothly. Subsequent theoretical analysis of the passability and dynamic simulation verification will be conducted to validate improvements in the operational efficiency and adaptability.

Currently, crawler chassis designs around the world are evolving toward greater intelligence and automation. For instance, some advanced crawler chassis incorporate autonomous driving technology, intelligent control systems, and new energy power systems, enhancing operational efficiency and environmental performance. Our design also reflects technological innovation to some extent, tailored to the actual needs of cotton planting and harvesting, as well as incorporating a hydraulic continuously variable transmission and rear-drive design. However, there is room for further enhancement in terms of intelligence and automation. In contrast, some general-purpose crawler chassis are designed to accommodate different working devices, enabling multiple operational functions and offering greater flexibility and adaptability.

5. Conclusions

(1) Considering the small planting area, relative dispersion, and difficulty in field transfer in the cotton planting regions of the Yangtze and Yellow River basins, this paper proposes a brush-roller-type cotton harvester with a crawler chassis designed to suit the 76 cm planting model and the harvesting requirement of spanning three rows. The chassis crawler gauge is set at 2000 mm, with a track width of 350 mm and a maximum ground clearance of the chassis set at 270 mm.

(2) The harvester employs a continuously variable transmission drive mode and rear-drive technology to adapt to complex terrain with an all-terrain dynamic drive. The maximum operating speed is 6.1 km/h, ensuring efficient power transfer and flexible adjustment. The chassis maintains efficient power transfer under various load and operational speed conditions. Considering the adaptability to various complex terrains during travel, an inverted trapezoidal crawler chassis is selected.

(3) Structural design and transmission selection for the brush-roller-type crawler cotton harvester's chassis were conducted, followed by a static structural simulation of the entire chassis frame using ANSYS Workbench. The results show that the stress distribution of the chassis's main load-bearing components generally conforms to the material's physical properties. The deformation cloud results indicate some stress concentration, but the amount of chassis deformation remains within an acceptable range, maintaining structural stability and safety.

(4) Field tests were conducted on the brush-roller-type crawler cotton harvester. The results show strong passability and stability in soft soil and sloped areas. The harvester is agile in field steering, with a timely transmission response. After multiple data tests, under various operational speeds, the harvester achieved a picking efficiency of 93%. Its speed control is excellent, allowing for flexible adjustment based on different cotton growth conditions and field environments.

Author Contributions: Conceptualization, Z.W. and C.C.; methodology, Z.W. and F.K.; software, Z.W. and Y.S.; validation, Z.W. and C.C.; formal analysis, Z.W. and C.C.; investigation, Z.W., F.K., Q.X. and C.C.; resources, Z.W. and C.C.; data curation, Z.W., F.K. and Q.X.; writing—original draft preparation, Z.W.; writing—review and editing, Z.W. and F.K.; visualization, Z.W. and Y.Z.; supervision, Z.W. and T.W.; project administration, C.C.; funding acquisition, C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Innovation Project of the Chinese Academy of Agricultural Sciences (31-NIAM-05) and the Integrated Pilot Project of Agricultural Machinery Research, Development, Manufacturing, Promotion, and Application in Xinjiang Uygur Autonomous Region (YTHSD2022-25).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: The authors thank the editor and anonymous reviewers for providing helpful suggestions for improving the quality of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wang, Z.W.; Gao, M.W.; Li, H.T.; Kong, F.J.; Lu, H.Q.; Wang, J.H.; Deng, Y.S.; Han, Z.; Shen, G.F.; Duan, B.; et al. Comparison of Appropriate Machine- Harvesting Traits of Different Cotton Varieties. *Shandong Agric. Sci.* **2017**, *49*, 24–28.
2. Chen, C.L.; Shi, L.; Zhang, Y.T.; Kong, F.T.; Xie, Q.; Sun, Y.F.; Huang, M.S. Design and Test of Cotton-boll Separation and Collection System from Stripper Cotton Harvester. *J. Agric. Sci. Technol.* **2017**, *19*, 68–73.
3. Chen, C.Q.; Jiang, F.; Zhang, X.J.; Zhang, G.Z.; Li, H. The Present Situation, Problems and Countermeasures of Mechanized Production of Cotton in China. *China Cott.* **2017**, *44*, 1–4.
4. Han, M.X.; Xu, K.; Liao, Y.T.; Li, M.; Yu, K. Co-simulation and Test of Electro–Hydraulic System of Novel Hybrid Track. *Trans. CSAM* **2024**, *55*, 396–408.
5. Wu, T.F. Steering Performance Test System for Small Remote-Controlled Tracked Tractor Design and Test. Master's Thesis, Sichuan Agricultural University, Ya'an, China, 2021.
6. Xu, G.W.; Song, Y.M.; Qiu, X.Y.; Liang, J.M.; Gao, Q.; Li, H. Matching Design and Test of Power System for Electric Self-propelled Crawler Chassis of Orchard. *Agric. Mech. Res.* **2022**, *44*, 251–255.
7. Grigore, L.Ș.; Oncioiu, I.; Priescu, I.; Joița, D. Development and Evaluation of the Traction Characteristics of a Crawler EOD Robot. *Appl. Sci.* **2021**, *11*, 3757. [CrossRef]
8. Liu, W.; Luo, X.; Zeng, S.; Zeng, L.; Wen, Z. The Design and Test of the Chassis of a Triangular Crawler-Type Ratooning Rice Harvester. *Agriculture* **2022**, *12*, 890. [CrossRef]
9. Zhao, J.Z.; Wang, F.C.; Yu, B.; Wang, D.C. Research on All-terrain Profiling Crawler Power Chassis. *Trans. CSAM* **2014**, *45*, 20–24.
10. Chen, Y.; Wang, Z.; Zhang, H.; Liu, X.; Li, H.; Sun, W.; Li, H. Investigation of the Traveling Performance of the Tracked Chassis of a Potato Combine Harvester in Hilly and Mountainous Areas. *Agriculture* **2024**, *12*, 1625. [CrossRef]
11. Xiong, Z.Q. Design and Optimization of Chassis Control System of Crawler Tractor. *Agric. Mech. Res.* **2023**, *45*, 259–264.
12. Zhao, J.Z.; Wang, F.C.; Zhu, Y.Q.; Zhang, X.Q.; Wang, D.C. Subsection Following Steering Control Strategy and Test of Hydrostatic-mechanical Driving Crawler Chassis. *Trans. CSAM* **2016**, *47*, 36–41.
13. Zhang, Z.G.; Wang, Y.C.; Li, H.Q.; Dao, F.; Zhang, Z.D.; Xue, H.T. Design and Test of Hydraulic Control Tracked Self-propelled Greenhouse Panax notoginseng Harvester. *Trans. CSAM* **2021**, *52*, 127–135.
14. Xie, B.; Wu, Z.B.; Mao, E.R. Development and Prospect of Key Technologies on Agricultural Tractor. *Trans. CSAM* **2018**, *49*, 1–17.
15. 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. *J. Comput. Electron. Agric.* **2020**, *173*, 105416. [CrossRef]
16. Wu, T.; Wu, H.B.; Liu, Q.T.; Liang, X.L.; Fan, Q.J.; Xie, C. Design and development of tracked sugarcane transporter. *J. Sugar Tech.* **2021**, *23*, 1137–1146. [CrossRef]
17. Sun, S.Y.; Wu, J.F.; Ren, C.L.; Tang, H.L.; Chen, J.W.; Ma, W.L.; Chu, J.W. Chassis trafficability simulation and experiment of a LY1352JP forest tracked vehicle. *J. For. Res.* **2021**, *32*, 1315–1325. [CrossRef]
18. Keller, T.; Arvidsson, J. A model for prediction of vertical stress distribution near the soil surface below rubber-tracked undercarriage systems fitted on agricultural vehicles. *J. Soil Till Res.* **2016**, *155*, 116–123. [CrossRef]
19. Wang, F.A.; Cao, Q.Z.; Li, Y.B.; Pang, Y.L.; Xie, K.T.; Zhang, Z.G. Design and Trafficability Experiment of Self-propelled Potato Harvester in Hilly and Mountainous Areas. *Trans. CSAM* **2023**, *54*, 10–19.
20. Wang, D.C.; Zhao, Y.R.; You, Y.; Zhang, X.N.; Wang, T.Y.; Li, S.B. Design and Experiment of Self–propelled Tracked Chassis of King Grass Harvester for Gentle Sloping Fields. *Trans. CSAM* **2023**, *54*, 178–187.
21. Li, S.J.; Chen, H.L.; Peng, J.B.; Meng, L.; Zhang, X.; Li, M.Z. Design and Test of Hydraulic Remote Control Crawler Power Chassis for Hilly and Mountainous Orchards. *Trans. CSAM* **2024**, *55*, 119–127.
22. 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. *Trans. CSAM* **2021**, *52*, 358–369.
23. Wang, T.; Liu, G.G.; Lou, T.T.; Yao, A.P.; Tong, Y.N.; Lei, C.L. Development and test of fruit tree branches grinder in hilly area. *J. Chin. Agric.* **2019**, *40*, 88–94.
24. Shi, R.; Dai, F.; Zhao, W.; Liu, X.; Wang, T.; Zhao, Y. Optimal Design and Testing of a Crawler-Type Flax Combine Harvester. *Agriculture* **2023**, *13*, 229. [CrossRef]

25. Gao, Q.M.; Pan, D.; Zhang, X.; Deng, F.Y.; Huang, D.H.; Wang, L.Q. Design and Simulation of Entire Track Modular Unmanned Agricultural Power Chassis. *Trans. CSAM* **2020**, *51*, 561–570.
26. Wang, M.; Zhao, B.; Wang, C.W.; Li, H.W.; Liu, Y.C.; Fang, X.F. Method for Controlling Turning Radius of Crawler-type Tractors Based on GMM. *Trans. CSAM* **2020**, *51*, 557–563.
27. Zhu, R.J.; Li, Y.M.; Xu, L.Z.; Liu, Y. Multi–objective Optimization Design of the Tracked Combine Harvester Chassis Frame. *Agric. Mech. Res.* **2023**, *45*, 36–43.
28. Hao, Z.H.; Yang, X.J.; Liu, L.J.; Yin, S.Z.; Liu, S.P.; Zhao, J.H. Design and Experiment of Multifunctional Dynamic Chassis for Orchard. *Trans. CSAM* **2018**, *49*, 66–73.
29. Qiu, B.J.; He, Y.J.; Sheng, Y.H.; Yin, Z.H.; Deng, W.Q. Finite Element Modal Analysis and Structure Optimization of Spray Boom. *Trans. CSAM* **2014**, *45*, 112–116.
30. Wang, J.W.; Tang, H.; Shen, H.G.; Bai, H.C.; Na, M.J. Design and experiment of high clearance roll-waist multifunctional power chassis for paddy field. *Trans. CSAE* **2017**, *33*, 32–40.
31. *GB/T 5262*; Measuring Methods for Agricultural Machinery Testing Conditions-General Rules. China National Standardization Administration Committee Press: Beijing, China, 2008.
32. Wang, Y.; Jin, C.; Yang, T.; Wang, T.; Ni, Y. Analysis and Experimental Investigation of Steering Kinematics of Driven Steering Crawler Harvester Chassis. *Agriculture* **2024**, *14*, 65. [CrossRef]
33. *GB/T 3871.5*; Agricultural Tractors—Test Procedures—Part 5: Turning and Clearance Diameters. China National Standardization Administration Committee Press: Beijing, China, 2006.