Design and optimization of a new terrain-adaptive hitch mechanism for hilly tractors

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Abstract: In view of the problems of poor working quality and low efficiency caused by traditional hitch mechanisms, which cannot make farm implements adapt to hillside fields for terrain-adaptive working after leveling the body of hilly tractors, a new type of terrain-adaptive hitch mechanism was designed which can adjust the transverse posture of farm implements to meet the ploughing requirements of complicated terrain in hilly and mountainous areas. The mechanism was mainly composed of the original hitch device and the newly added rotating device. The kinematic model of each sub-mechanism was established, as well as the mathematical relation of significant performance indexes of the whole mechanism, such as lifting capacity, transverse inclination angle and tillage depth. Genetic algorithm was used to optimize the lifting performance of this hitch mechanism in Matlab, so that the minimum vertical lifting force at the center of gravity of farm implements increased by 14.1%, which met the requirements of national standards. Through ADAMS simulation calculation, it was found that different working slopes had a certain influence on the external load of each component, and terrain-adaptive hitch mechanism had little effect on the vibration characteristics of hilly tractors. The fatigue analysis and optimization design of the key component, rotating shaft, were carried out in ANSYS Workbench, and the mass of this part reduced by 64%. A real vehicle test platform was set up to test and verify the power lifting range and working slope range of terrain-adaptive hitch mechanism. The test results showed that the actual power lifting ranged in 185-857 mm, and the maximum error from the theoretical range was only 3.1%, while the actual working slope range was from –25.9° to +23.2°, and the maximum error from the theoretical range was only 4.5%. Therefore, the terrain-adaptive hitch mechanism can meet the requirements of power lifting performance, and simultaneously can adjust the transverse posture of farm implements for adapting to hillside fields of no less than 20°.
Keywords: hilly tractors, hitch mechanism, terrain-adaptive working, transverse posture, optimal design
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1 Introduction

As the main production base of grain, oil and other crops in China, hilly and mountainous areas account for more than 43% of the country's land and more than 50% of the country's population[1,2]. However, due to the influence of natural environment and economic conditions, the agricultural machinery and equipment suitable for working in hilly and mountainous areas are very scarce, which seriously restricts the development of agricultural mechanization. Tractors are prone to sideslip and rollover, uneven tillage depth and other problems when ploughing on hillside fields, which the safety, quality and efficiency cannot be guaranteed. The leveling technology of tractor body and the transverse posture adjustment technology of farm implements can realize terrain-adaptive working, and effectively overcome the above drawbacks, which is a promising direction of agricultural mechanization development in hilly and mountainous areas of China.

In western developed countries, hilly tractors with low ground clearance, wide wheelbase and automatic body leveling system are mainly studied, and there are some accumulation in intelligent design and electronic control[3-7]. In the aspect of hitch mechanisms, a number of new devices suitable for hilly and mountainous areas have emerged, and a great deal of research has been done on the attitude adjustment of farm implements and the stability of tractor operation[8-13]. However, foreign hilly tractors, especially in Europe and North America, have strong power and large size, their direct introduction and use cannot well adapt to the complex hilly and mountainous terrain in China.

Based on the current situation of cultivated land and agricultural mechanization level in China, the state has set up a special research project on hilly tractors in the 13th Five-Year Plan, and medium-sized power hilly tractors have been paid more attention. At present, there are many studies[14-18] on the leveling technology of tractor body in China, while studies on the transverse posture adjustment technology of farm implements are relatively few. Zhou et al.[19] designed an automatic leveling system of rotary tillers, and it was verified by tests that the ground flatness was significantly improved and the tillage depth was more stable after the rotary tiller equipped with this system. Wang[20] invented an automatic leveling leveler of tractor traction plate, which used the negative feedback of a level sensor to implement closed-loop control, and it met the leveling requirements of the whole device. Yang et al.[21] proposed an automatic measurement method of tillage depth based on hilly tractors with body leveling function. The actual tillage depth can be obtained by collecting the signals of sensors in

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real time, so that the automatic measurement of tillage depth can be realized successfully. Liu[22] developed a kind of hitch mechanism with one-side hydraulic cylinder adjustment, which was characterized by replacing lifting rods with two hydraulic cylinders. This mechanism connected the rodless cavity of cylinders with an oil pipe, and level farm implements by controlling the oil in and out of one side of cylinders. Jiang et al.[23] designed an electric power controlled hydraulic hitch system for tractors in hills and mountains, and analyzed its operating mechanism and control method. The simulation analysis results showed that the speed and displacement were controlled within 5% error. Shao et al.[24] developed a type of hitch mechanism with simultaneous adjustment of two hydraulic cylinders on both sides, which was characterized in that hydraulic cylinders moved in the same direction to lift or drop farm implements, while the reverse movement could change the transverse inclination angle of farm implements. The fuzzy PID control algorithm was adopted to make farm implements basically adapt to hilly terrain. Yang et al.[25] designed a collaborative control system for tractor body and farm implement attitude based on the mountain crawler tractor developed by their team. By using PID algorithm and double closed-loop fuzzy PID algorithm for the control of the tractor body and farm implement respectively, the accuracy and stability of the attitude cooperative control system can meet the requirements of hillside contour operation.

From the above description, it can be seen that in order to realize the attitude adjustment function of farm implements, scholars mainly focus on farm implements and hitch mechanisms. However, it is difficult to popularize and apply a specific farm implement with adjustable transverse posture because of its high development cost and non-universality. Moreover, there have been many studies on the control performance of hitch mechanisms, and the hitch mechanism, as the executive component of the control system, is the basis for the realization of the whole system function. Therefore, the hitch mechanism, which plays the role of connecting members, transmitting forces and controlling motion between the tractor body and the farm implement, has become another research object to realize the adjustable transverse posture of farm implements. The terrain-adaptive hitch mechanism can be used to attach a variety of farm implements, which meets the different ploughing requirements of hilly tractors, so it has important research significance and practical value. Aiming at the problem that hilly tractors are difficult to adjust the transverse posture of farm implements, this paper adopts the research methods of theoretical analysis, simulation optimization and experimental verification to design a new type of terrain-adaptive hitch mechanism in order to ensure that farm implements have eximious copying ability when working on hillside fields.

2 Overall design of terrain-adaptive hitch mechanism

Taking a 40 horsepower agricultural wheeled tractor of Shandong Wuzheng Group as a prototype, it is equipped with a type 1 rear-mounted three-point hitch device, and is connected with a 1L-325 plough. The engine rated power is 29.4 kW. According to GB/T 1593-2015, it is calculated that the lifting capacity of hitch mechanism should not be less than 6615 N. From the perspective of agricultural mechanization, the suitable terrain for ploughing in hilly and mountainous areas is the hilly land of 6° to 15° and the sloping land of 15° to 25°[1]. Therefore, the main design objectives of terrain-adaptive hitch mechanism are that the lifting capacity of electro-hydraulic hoist is not less than 7000 N and the working slope is not less than 20°.

Traditional hitch mechanisms cannot adjust the transverse posture of farm implements. Although some scholars have tried to improve traditional hitch mechanisms, such as replacing lifting rods with hydraulic cylinders, this kind of hitch mechanism has serious kinematic interference problems, for example, the farm implement also has a large translation while twisting, which is prone to jamming and even parts damage. Therefore, it is difficult to meet the ploughing requirements of complex terrain in hilly and mountainous areas. For this reason, an innovative mechanical design scheme is proposed, that is, a rotating device is added between the hitch device and the farm implement, which together form a new type of terrain-adaptive hitch mechanism, as shown in Figure 1. As an intermediate medium connecting the hitch device and farm implement, the rotating device is used to independently adjust the transverse posture of farm implements. The motionless bracket is connected with the hitch device, and the movable part is connected with the farm implement. The hydraulic cylinder outputs power to make the movable part deflect relative to the bracket around a rotating shaft, thus driving the farm implement to adapt to the terrain with a certain slope at the same transverse inclination angle.

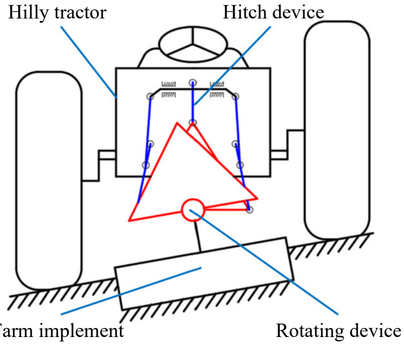
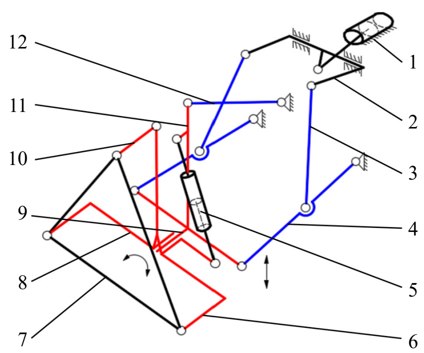


Figure 1 Functional diagram of terrain-adaptive hitch mechanism

The composition of terrain-adaptive hitch mechanism is shown in Figure 2. The hitch device comprises two lifting rods, an upper pull bar and two lower pull bars. The rotating device comprises a rotating bracket, a rotating body and a rotating shaft. The power sources are two hydraulic cylinders. The front end of the rotating bracket is connected with hitch rods, and the rear end supports the rotating body through the rotating shaft. The upper end of the rotating hydraulic cylinder is hinged with the rotating bracket, and the lower end is hinged with the rotating body. The rotating body is connected with the farm implement through the upper and lower linkers, as a result the rotating movement is transmitted to the farm implement.



1. Lifting hydraulic cylinder 2. Lifting arm 3. Lifting rod 4. Lower pull bar 5. Rotating hydraulic cylinder 6. Lower linker 7. Farm implement 8. Rotating body 9. Rotating shaft 10. Upper linker 11. Rotating bracket 12. Upper pull bar

Figure 2 Composition of terrain-adaptive hitch mechanism

The innovation of this design is that the spatial motion of farm implements is decomposed into a lifting motion in the longitudinal plane and a rotating motion in the transverse plane, hence the new type of mechanism is essentially a spatial mechanism with two degrees of freedom. The disadvantage of this mechanism is that its structure is a little complex, but it is easy to establish the mathematical model and to control the attitude of farm implements accurately, making it work more reliably.

3 Mathematical modeling of terrain-adaptive hitch mechanism

The purpose of establishing the mathematical model of terrain-adaptive hitch mechanism is to clarify the geometric relation and motion law of each member, which can be used as the theoretical basis for determining the overall size of this mechanism. The terrain-adaptive hitch mechanism is a kind of spatial mechanism, but considering its symmetry, in order to facilitate research, each rod can be projected in the longitudinal plane of tractor body for analysis, which is approximately simplified as the plane motion of a rigid body[26].

3.1 Power lifting mechanism

The power lifting mechanism is an offset crank-slider mechanism composed of a lifting hydraulic cylinder, a piston push rod, an inner lifting arm and the tractor body, as shown in Figure 3.

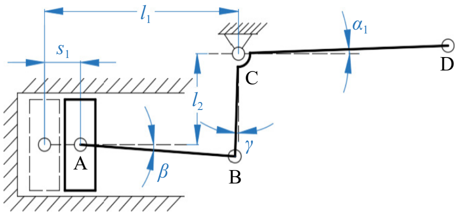


Figure 3 Kinematic diagram of power lifting mechanism

The geometric relation is obtained from the graph

$$\begin{cases} l_{\mathrm{AB}} \cdot \cos\beta + l_{\mathrm{BC}} \cdot \sin\gamma + s_1 = l_1 \\ l_{\mathrm{BC}} \cdot \cos\gamma - l_{\mathrm{AB}} \cdot \sin\beta = l_2 \end{cases} \tag{1}$$

where, S_1 is the piston displacement of the lifting hydraulic cylinder, m. The velocity relation can be obtained by differentiating Equation (1)

$$i_{\alpha_1} = \frac{\dot{\alpha}_1}{\dot{s}_1} = \frac{1}{l_{\mathrm{BC}}(\cos\gamma + \sin\gamma\tan\beta)} \tag{2}$$

where, i_{α_1} is the transmission ratio of the outer lifting arm to the piston of the lifting hydraulic cylinder.

3.2 Inclination adjusting mechanism

The inclination adjusting mechanism is a swinging guide rod mechanism composed of a rotating hydraulic cylinder, a piston push rod, a rotating arm and a rotating bracket in the transverse plane, as shown in Figure 4. The transverse inclination angle characterizes the tilt degree of transverse posture of farm implements and the adaptive range of working slopes, which is a unique performance index of terrain-adaptive hitch mechanism and reflects its copying ability.

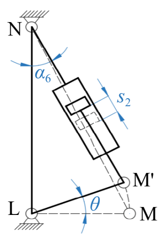


Figure 4 Kinematic diagram of inclination adjustment mechanism

The geometric relation is obtained from the graph

$$\begin{cases} l_{\mathrm{LM'}} \cdot \cos\theta = l_{\mathrm{M'N}} \cdot \sin\alpha_6 \\ l_{\mathrm{LM'}} \cdot \sin\theta + l_{\mathrm{M'N}} \cdot \cos\alpha_6 = l_{\mathrm{LN}} \end{cases} \tag{3}$$

$$l_{\mathrm{LM'}} = l_{\mathrm{LM}};\ \ l_{\mathrm{M'N}} = l_{\mathrm{MN}} - s_2 \tag{4}$$

where, S_2 is the piston displacement of the rotating hydraulic cylinder, m. The angular relation solved by Equation (5)

$$\theta = \arcsin\frac{l_{\mathrm{LN}}^2 + l_{\mathrm{LM}}^2 - (l_{\mathrm{MN}} - s_2)^2}{2l_{\mathrm{LN}}l_{\mathrm{LM}}} \tag{5}$$

where, θ is the included angle between the rotating arm and the horizontal line, and its value is equal to the transverse inclination angle of the farm implement, (°).

3.3 Terrain-adaptive hitch mechanism

In the quadrilateral CDEF, an outer lifting arm, a lifting rod, a lower pull bar and the tractor body form a crank-rocker mechanism. The geometric relation is obtained from the graph

$$\begin{cases} l_{\mathrm{CF}x} + l_{\mathrm{EF}} \cdot \cos\alpha_2 = l_{\mathrm{CD}} \cdot \cos\alpha_1 + l_{\mathrm{DE}} \cdot \sin\alpha_3 \\ l_{\mathrm{CF}y} + l_{\mathrm{CD}} \cdot \sin\alpha_1 = l_{\mathrm{EF}} \cdot \sin\alpha_2 + l_{\mathrm{DE}} \cdot \cos\alpha_3 \end{cases} \tag{6}$$

The velocity relation can be obtained by differentiating Equation (6)

$$i_{\alpha_2} = \frac{\dot{\alpha}_2}{\dot{s}_1} = \frac{l_{\mathrm{CD}}(\sin\alpha_1 + \cos\alpha_1\cot\alpha_3)}{l_{\mathrm{EF}}(\sin\alpha_2 + \cos\alpha_2\cot\alpha_3)} i_{\alpha_1} \tag{7}$$

where, i_{α_2} is the transmission ratio of the lower pull bar to the piston of the lifting hydraulic cylinder.

In the quadrilateral FGHI, a lower pull bar, a rotating bracket, an upper pull bar and the tractor body form a double rocker mechanism. The geometric relation is obtained from the graph

$$\begin{cases} l_{\mathrm{FI}x} + l_{\mathrm{HI}} \cdot \cos\alpha_4 = l_{\mathrm{FG}} \cdot \cos\alpha_2 + l_{\mathrm{GH}} \cdot \sin\alpha_5 \\ l_{\mathrm{FI}y} + l_{\mathrm{HI}} \cdot \sin\alpha_4 = l_{\mathrm{FG}} \cdot \sin\alpha_2 + l_{\mathrm{GH}} \cdot \cos\alpha_5 \end{cases} \tag{8}$$

The velocity relation can be obtained by differentiating Equation (8)

$$i_{\varphi} = \frac{\dot{\varphi}}{\dot{s}_1} = -\frac{l_{\mathrm{FG}}(\sin\alpha_2 - \cos\alpha_2\tan\alpha_4)}{l_{\mathrm{GH}}(\cos\alpha_5 - \sin\alpha_5\tan\alpha_4)} i_{\alpha_2} \tag{9}$$

where, i_{φ} is the transmission ratio of the rotating bracket to the piston of the lifting hydraulic cylinder.

3.4 Lifting stroke, lifting speed ratio and lifting capacity

The lifting stroke, lifting speed ratio and lifting capacity are significant indexes reflecting the lifting performance of hitch mechanisms[26]. The lifting stroke refers to the movement of the lower hitch point in the vertical direction corresponding to the full piston stroke of the lifting hydraulic cylinder. The lifting speed ratio refers to the ratio of vertical lifting speed at the center of gravity of farm implements to the piston moving speed of the lifting hydraulic cylinder. According to national standards, the lifting capacity is expressed by the vertical lifting force acting 610 mm behind the lower hitch point, which is approximately regarded as the center of gravity of farm implements[27,28].

The expression can be obtained from Figure 5

$$\begin{cases} y_{\mathrm{T}} = l_3 + l_{\mathrm{FG}}\sin\alpha_2 + l_{\mathrm{GT}}\sin\varphi \\ s_{\mathrm{T}} = y_{\mathrm{T\,max}} - y_{\mathrm{T\,min}} \end{cases} \tag{10}$$

where, S_{T} is the lifting stroke of the lower hitch point.

$$\begin{cases} y_{\mathrm{g}} = l_3 + l_{\mathrm{FG}}\sin\alpha_2 + (l_{\mathrm{GT}} + l_5)\sin\varphi \\ i_{\mathrm{g}} = \dfrac{\dot{y}_{\mathrm{g}}}{\dot{s}_1} = i_{\alpha_2} l_{\mathrm{FG}}\cos\alpha_2 + i_{\alpha_5}(l_{\mathrm{GT}} + l_5)\cos\varphi \end{cases} \tag{11}$$

where, i_{g} is the lifting speed ratio at 610 mm behind the lower hitch point.

$$F_g = \frac{\pi D^2 P \eta_1 \eta_2}{4 i_g} \tag{12}$$

where, D is the inner diameter of the lifting hydraulic cylinder, m; P is the rated working pressure of the hydraulic system, MPa; η_1 is the transmission efficiency of the lifting hydraulic cylinder; η_2 is the mechanical efficiency of terrain-adaptive hitch mechanism, and F_g is the vertical lifting force at 610 mm behind the hitch mechanism, kN.

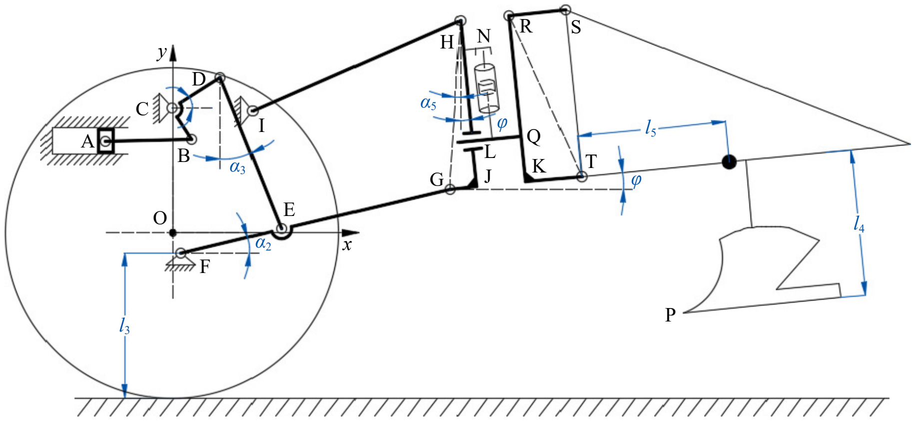


Figure 5 Kinematic diagram of terrain-adaptive hitch mechanism

3.5 Tillage depth

The distance between the furrow bottom and the soil surface is called the tillage depth when tractors work normally. Multi-ploughs require the same depth of each plough, that is, the plough frame should be parallel to the ground. The terrain-adaptive hitch mechanism should be able to make farm implements reach the predetermined tillage depth and keep good uniformity. The tillage depth relation in the longitudinal plane can be expressed as

$$h_P = l_4 - (l_3 - l_{FG}\sin(-\alpha_2)) \tag{13}$$

where, h_P is the tillage depth when ploughing on the horizontal ground (m), which is expressed as a positive value generally.

Before hilly tractors work along contour lines on hillside fields in hilly and mountainous areas, the rotating device adjusts the transverse inclination angle of farm implements to keep the same with hillside fields, and then ploughs are buried into soil. Figure 6 shows the schematic diagram of tillage depth analysis in the transverse plane.

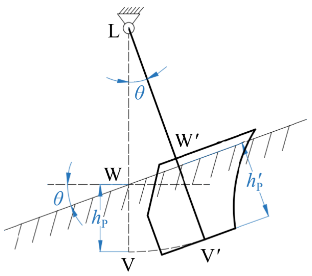


Figure 6 Schematic diagram of tillage depth analysis in the transverse plane

The expression can be obtained from the graph

$$h'_P = l_{LV} - (l_{LV} - h_p)\cos\theta \tag{14}$$

where, h'_P is the tillage depth when ploughing on the hillside land, m.

4 Performance analysis of terrain-adaptive hitch mechanism

The main technical parameters of the tractor and farm implement are listed in Tables 1 and 2 respectively. By bringing the technical parameters of the tractor and farm implement and the design parameters of the hitch device and rotating device into the mathematical model, and solving them by Matlab programming, the inherent laws of terrain-adaptive hitch mechanism can be obtained, providing data support for its performance analysis and structural improvement.

Table 1 Main technical parameters of tractor

Parameter	Value
Engine rated power /kW	29.4
Rated working pressure of hydraulic system P/MPa	16
Oil pump flow / (L·min^{-1})	20
Inner diameter of lifting hydraulic cylinder D/mm	80
Piston stroke of lifting hydraulic cylinder s_1/mm	100
Transmission efficiency of lifting hydraulic cylinder η_1	0.85

Table 2 Main technical parameters of farm implement

Parameter	Value
Number of ploughs n	3
Single plough width b/mm	250
Tillage depth h_P/mm	250-300
Machine mass/kg	140
Adaptive soil specific resistance k/kPa	40-60

The original hitch rods of Wuzheng's tractor are used, which can not only ensure that the instantaneous movement center of the hitch mechanism is within a reasonable range, but also keep the soil penetration capacity of farm implements unchanged. Besides, it can save the development cost and improve the product economy, too. The front and rear end of the rotating device are connected with the hitch device and farm implement respectively, so the overall size of the rotating device can be determined in the light of technical parameters of the hitch device and farm implement. The main design parameters of terrain-adaptive hitch mechanism are listed in Table 3.

4.1 Lifting capacity analysis

National standards clearly stipulate the lifting capacity of hitch mechanisms, so the lifting capacity analysis of terrain-adaptive hitch mechanism should be carried out first. Only when the design parameters of each rod meet the lifting performance requirements, other performance analysis is meaningful, otherwise, tractors will not work normally. Based on Equation (12), the curves of the vertical lifting force of two hitch mechanisms changing with the piston displacement of the lifting hydraulic cylinder can be obtained, as shown in Figure 7.

Table 3 Design parameters of terrain-adaptive hitch mechanism

parameter	value
Length of lifting rod l_{DE}/mm	532
Length of the front segment of lower pull bar l_{EF}/mm	355
Length of lower pull bar l_{FG}/mm	820
Length of upper pull bar l_{HI}/mm	664
Vertical installation distance of rotating hydraulic cylinder l_{LN}/mm	280
Length of rotating arm l_{LM}/mm	135
Mechanical efficiency η_2	0.90

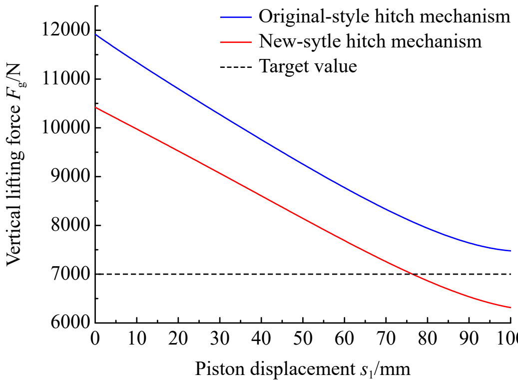


Figure 7 Curves of vertical lifting force of two hitch mechanisms

It can be seen from the figure that the change trend of vertical lifting force curves of the original hitch mechanism and the new hitch mechanism is the same, that is, the vertical lifting force gradually decreases with the increasing piston displacement of the lifting hydraulic cylinder. The vertical lifting forces of the original and new hitch mechanism differ by about 1000 N at the same piston position, and both reach the minimum at the end of the piston stroke, with the minimum values of 7478.0 N and 6315.5 N respectively. Obviously, the lifting capacity of this new hitch mechanism does not reach the design target of 7000 N, indicating that the terrain-adaptive hitch mechanism which is directly equipped with the rotating device at the rear end of the original hitch device cannot meet the lifting performance requirements and needs to be further optimized.

4.2 Lifting capacity optimization

Under the situation where hydraulic parameters have been determined, the vertical lifting force of terrain-adaptive hitch mechanism at the center of gravity of farm implements is very important. In the whole lifting stroke range, the greater the maximum vertical lifting force, the better the lifting performance of hitch mechanisms. In the optimization mathematical model, the lengths of hitch rods are taken as design variables, the vertical lifting force at 610 mm behind the lower hitch point is taken as an objective function, and the requirements of national standards and long-term accumulated practical experience are taken as constraints.

Design variables are the crucial members that affect the lifting capacity, namely

$$x = [l_{DE}, l_{EF}, l_{FG}, l_{HI}]^T \tag{15}$$

The objective function can be expressed as

$$\min f(x) = -F_{g\min} \tag{16}$$

where, $F_{g\min}$ is the minimum vertical lifting force at the center of gravity of the farm implement in the whole power lifting range.

Constraints should include boundary constraints of design variables, geometric constraints of the four-bar mechanism and performance constraints of terrain-adaptive hitch mechanism.

The terrain-adaptive hitch mechanism adds a rotating device at the rear end of the original hitch rods, which leads to the extension of the new hitch point backward. In order to minimize the influence of this change on the passing performance of hilly tractors, the longitudinal length of hitch rods should be appropriately reduced. Therefore, the size range of hitch rods can be preliminarily determined. The length range of the lifting rod is unchanged at 440 mm $\leq l_{DE} \leq$ 560 mm. The front segment length range of the lower pull bar is 174 mm $\leq l_{EF} \leq$ 355 mm. The length range of the lower pull bar is 355 mm $\leq l_{FG} \leq$ 820 mm. The length range of the upper pull bar is 400 mm $\leq l_{HI} \leq$ 500 mm. The upper and lower limits of design variables, i.e., boundary constraints, can be expressed as

$$\begin{cases} g_j(x_i) = x_i - U_i \leq 0 \ (i = 1,2,3,4; j = i) \\ g_j(x_i) = D_i - x_i \leq 0 \ (i = 1,2,3,4; j = i+4) \end{cases} \tag{17}$$

where, U_i is the upper bound of design variables; and D_i is the lower bound of design variables. On the basis of crank existence condition, i.e., geometric constraints, the CDEF of the four-bar mechanism in Figure 5 must satisfy

$$\begin{cases} g_9(x) = l_{CD} - l_{DE} \leq 0 \\ g_{10}(x) = l_{CD} - l_{EF} \leq 0 \\ g_{11}(x) = l_{CD} - l_{FG} \leq 0 \\ g_{12}(x) = l_{CD} + l_{DE} - l_{EF} - l_{FG} \leq 0 \\ g_{13}(x) = l_{CD} + l_{EF} - l_{DE} - l_{FG} \leq 0 \\ g_{14}(x) = l_{CD} + l_{FG} - l_{EF} - l_{DE} \leq 0 \end{cases} \tag{18}$$

According to the regulations in GB/T 1593–2015, i.e., performance constraint, the lifting stroke of type 1 hitch mechanism should match the following equation:

$$g_{15}(x) = 610 - s_T \leq 0 \tag{19}$$

In terms of the optimization mathematical model, the lifting capacity optimization of terrain-adaptive hitch mechanism is a nonlinear programming problem, that is, solving the minimum value of the nonlinear multivariate function under constraint conditions. Therefore, in this paper, the global optimization toolbox of Matlab R2016b is employed, and the widely used genetic algorithm is selected to globally optimize the lifting capacity[29]. After several rounds of tuning, the attribute settings of the genetic algorithm are determined. Specify creation function to feasible population in the population panel, scaling function to top in the fitness scaling panel, and mutation function to adaptive feasible in the mutation panel. Moreover, set crossover function to heuristic in the crossover option, nonlinear constraint algorithm to penalty in the constraint parameters option, and generations to 800 in the stopping criteria. Select best fitness in the plot functions lastly. And keep the remaining options as the default. Before solving the optimization mathematical model, the Rastrigin's function embedded in Matlab is used to test the convergence and robustness of the genetic algorithm. Through testing, the program found the minimum value of 0 after about 200 iterations, and two design variables are both 0, which is completely consistent with the analytical solution. The evolution curves of the best fitness value and average fitness value are obtained eventually after the program calculation is finished, as shown in Figure 8. The optimization results of design variables and the objective function are shown in Table 4 and Figure 9 respectively.

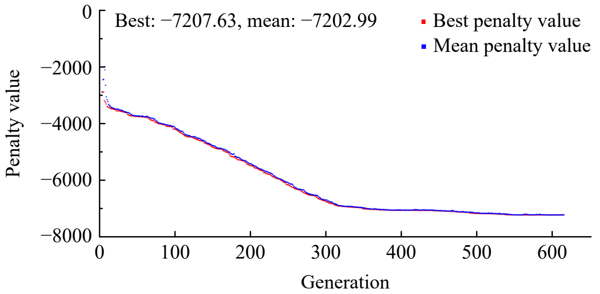


Figure 8 Evolution curves of fitness value

Table 4 Comparison of data before and after optimization of design variables

Design variable	Lifting rod l_{DE}/mm	Front segment of lower pull bar l_{EF}/mm	Lower pull bar l_{FG}/mm	Upper pull bar l_{HI}/mm
Before optimization	532	355	820	664
After optimization	525.76	256.94	634.77	499.98

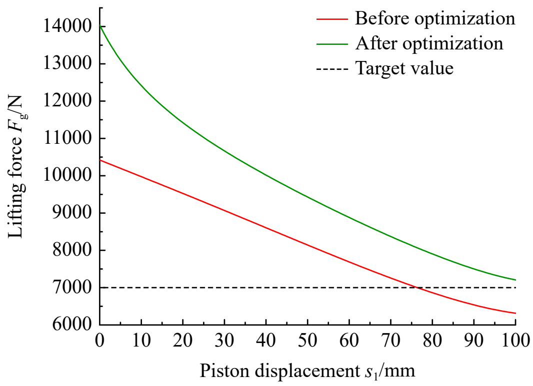


Figure 9 Curves of vertical lifting force before and after optimization

It can be seen from the figure that the lifting capacity of terrain-adaptive hitch mechanism is effectively improved, which is in line with expectations. The minimum vertical lifting force before optimization is 6315.5 N, while the minimum vertical lifting force after optimization is 7207.6 N, which reaches the design target of 7000 N. After optimization, the vertical lifting force is 14.1% higher than that before optimization, so the lifting performance of the new hitch mechanism is obviously improved.

4.3 Transverse inclination and tillage depth analysis

Based on Equation (5), the curve of transverse inclination angle of the farm implement changing with the piston displacement of the rotating hydraulic cylinder can be obtained, as shown in Figure 10. It can be seen from the figure that in the design range of negative 20° to positive 20°, the linearity between the transverse inclination angle and the piston displacement is high, which is beneficial to the realization of electro-hydraulic control. The piston displacement corresponding to the transverse inclination angle falls within the interval of [–39.2, 44.9]. In order to facilitate the selection of the rotating hydraulic cylinder, the piston displacement interval is expanded to [–50, 50], so the piston stroke is 100 mm. At this moment, the theoretical range of transverse inclination angle of the farm implement is negative 26.4° to positive 22.2°, that is, the adaptable working slope is greater than 20°, which reaches the design target.

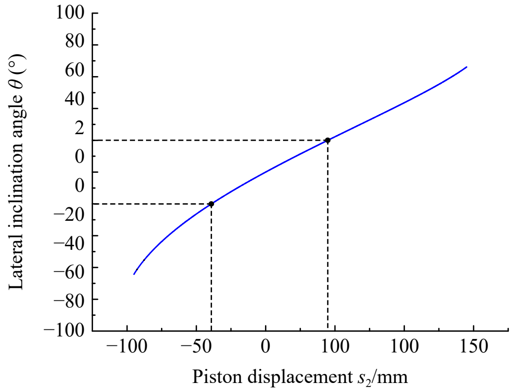


Figure 10 Transverse inclination angle curve

When hilly tractors work on hillside fields in hilly and mountainous areas, the tillage depth is not only controlled by the lifting hydraulic cylinder, but also influenced by the rotating hydraulic cylinder. Expression (14) can be abstracted into a binary function $h'_P = f(s_1, s_2)$. The tillage depth is determined by the piston displacement of two cylinders at the same time, and its change rule is shown in Figure 11. It can be seen from the figure that when the piston displacement S_2 is constant, the tillage depth decreases with the increase of the piston displacement S_1, which has the linear relation approximately. When the piston displacement S_1 is constant, the tillage depth increases with the increase of the piston displacement S_2, which has symmetrical distribution approximately. When ploughing on the horizontal ground, the maximum tillage depth can reach 380.7 mm, which can meet the requirements of shallow ploughing, intermediate ploughing and deep ploughing.

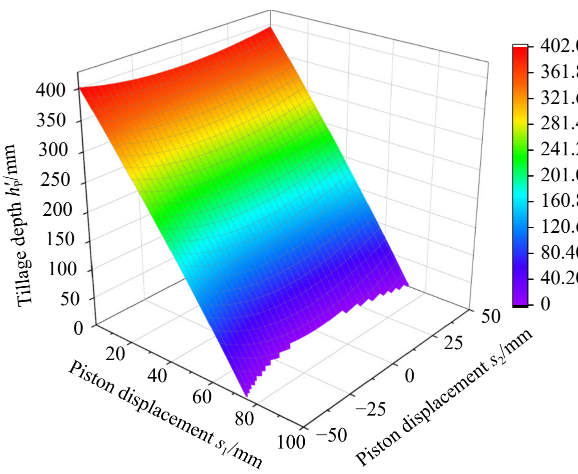
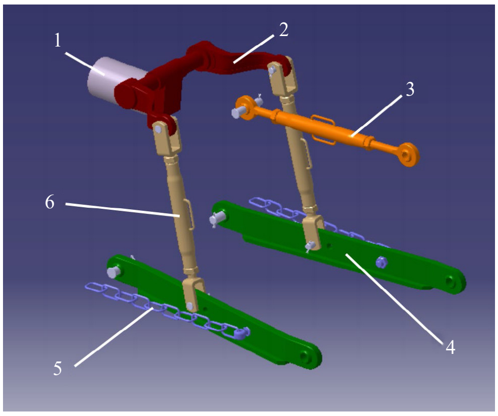


Figure 11 Variation law of tillage depth

5 Simulation analysis and structural optimization of terrain-adaptive hitch mechanism

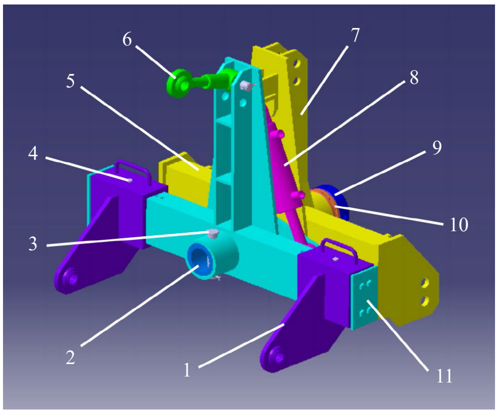
5.1 Structural design

The original design is adopted for hitch rods, which adjust the longitudinal length only according to the passing performance requirements, and other structural sizes are not changed. The rotating device, which belongs to non-standard device, has great flexibility in design in details. In the early stage, the structure of parts can be initially determined on the basis of design experience, and then the strength can be checked and the structure can be further optimized by using the finite element method. A three-dimensional model of terrain-adaptive hitch mechanism is established in the Part Design module of CATIA, as shown in Figure 12.



1. Lifting hydraulic cylinder 2. Lifting arm 3. Upper pull bar
4. Lower pull bar 5. Anchoring chain 6. Lifting rod

a. Hitch device



1. Lower linker 2. Rotating shaft 3. Axle pin 4. Alignment pin
5. Rotating body 6. Upper linker 7. Rotating bracket
8. Rotating hydraulic cylinder 9. Bearing threaded end cap
10. Thrust ball bearing 11. Baffle b. Rotating device

b. Rotating device

Figure 12 Three-dimensional model of terrain-adaptive hitch mechanism

The rotating device is welded by steel plates, in which the hydraulic cylinder, bearings, bolts and pins are standard parts, which can be directly selected. One end of the rotating bracket is used to connect hitch rods, and the other end is connected to the rotating body. The rotating body is sheathed on the rotating shaft and their relative position is fixed by the pin shaft. The rotating shaft is installed on the rotating bracket, supported by a sliding bearing and axially positioned by a bearing end cover with internal threads. A thrust ball bearing is installed between the bearing end cover and the rotating bracket to reduce friction in relative motion. One end of the upper and lower linkers is connected to the rotating body, and the other end is connected to the farm implement.

5.2 Load analysis

The purpose of load analysis is to clarify mechanical characteristics of terrain-adaptive hitch mechanism of hilly tractors during ploughing on hillside fields, such as calculating the binding forces of each hinged joint, and then complete the load decomposition to provide data for the strength check of key force-bearing components.

The loads of ploughs in practical ploughing is very complex, which generally needs to be measured by the six-component test device[30]. In the simulation analysis stage, the empirical formula can also be used as approximate estimation of soil resistance[31]. Soil resistance in the horizontal, vertical and transverse directions is

$$\begin{cases} R_x \approx nbkh'_{\mathrm{P}} \\ R_y \approx -8.89h'_{\mathrm{P}}(h'_{\mathrm{P}}-0.3)R_x + 0.05R_x \\ R_z \approx 0.3R_x \end{cases} \tag{20}$$

where, n is the number of ploughs; b is the width of each plough, and k is soil specific resistance.

Assuming that the tillage depth of hilly tractors is 275 mm and the soil specific resistance is 0.05 N/mm² when ploughing on the horizontal ground, it can be known from Equations (14) and (20) that the soil resistance of ploughs is a univariate function of the ground slope. For the time being, this paper doesn't consider the influences of technical parameters of the farm implement and the changes of soil properties, and only pay attention to the load of terrain-adaptive hitch mechanism when hilly tractors work on different hillside fields.

The three-dimensional model is imported into ADAMS/View module, and geometric model processing, material attribute setting, kinematic pair and drive definition, external load addition and other steps are carried out in turn, as shown in Figure 13. In simulation calculation, the piston displacement of the lifting hydraulic cylinder remains unchanged, and the moving speed of the rotating hydraulic cylinder piston is set to 1 mm/s, so that the farm implement rotates slowly, which can be regarded as a quasi-static equilibrium process. After automatic solution by the software, the result data is measured in the Post-Processing module of ADAMS, and the load curves of each hinge joint are obtained, as shown in Figure 14.

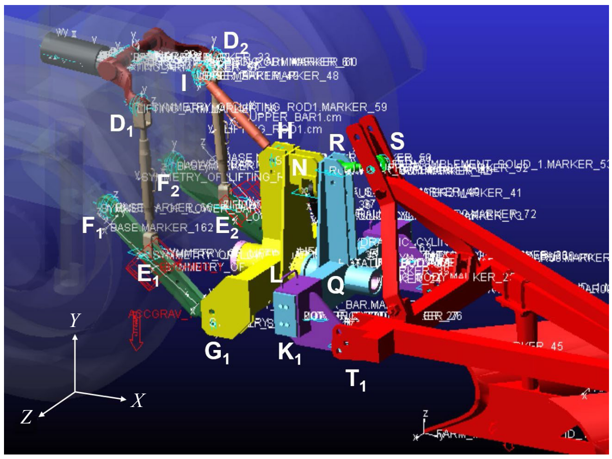


Figure 13 Simulation model of terrain-adaptive hitch mechanism

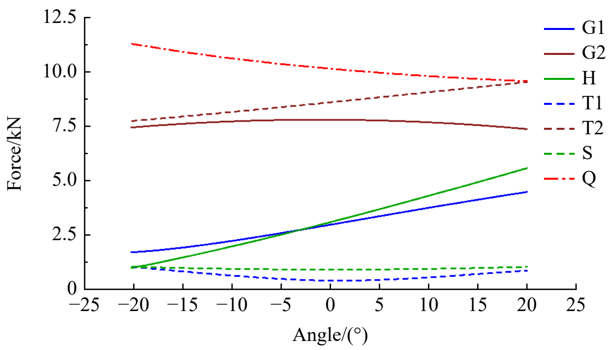


Figure 14 Binding forces at each hinge joint

It can be seen from the figure that different working slopes have a certain influence on the loads of each component, and the degree is different. For example, the maximum difference of binding force at the left lower linker T1 is only 642.8 N, which has little effect, so the load value when ground slope is 0° can be approximately taken as the external load of this part. On the other hand, the maximum difference of binding force at the connection point Q between the rotating body and the rotating shaft is as high as 1717.5 N, so the effect of ground slope cannot be ignored. When checking the structural strength of the rotating shaft, the maximum force value of negative 20° should be taken as the external load.

Due to the addition of a rotating device to the new hitch mechanism, the weight of the working device at the rear end of the tractor will increase by 110 kg and the center of gravity will move backward by 205 mm. These differences may affect the dynamic characteristics of tractor system[32,33]. In order to quantify this influence, the vibration analysis of the hilly tractor equipped with terrain-adaptive hitch mechanism is further carried out. The tractor vibration system is appropriately simplified to grasp the main contradiction quickly. And the related parameters of tractor vibration system are listed in Table 5.

Table 5 Parameters of tractor vibration system

Parameter	Value
Tire stiffness of front wheel/N·mm^{-1}	331.21
Tire damping of front wheel/N·s·mm^{-1}	1.95
Tire stiffness of rear wheel/N·mm^{-1}	368.23
Tire damping of rear wheel/N·s·mm^{-1}	2.06
Seat suspension stiffness/N·mm^{-1}	34.50
Seat suspension damping/N·s·mm^{-1}	1.21
Seat cushion stiffness/N·mm^{-1}	75.50
Seat cushion damping/N·s·mm^{-1}	3.84
Tractor mass/kg	1344
Seat mass/kg	27
Driver mass/kg	66

The input and output channels of tractor vibration system are established in ADAMS/Vibration module. Define sinusoidal excitation at the grounding point of four wheels as input signals, and the driver's vertical acceleration as output signals. And then a vibration analysis test was conducted by setting the amplitude of 10 mm, the frequency of 0.1-100 Hz and the number of steps of 5000. The frequency responses at the driver's centroid are shown in Figure 15.

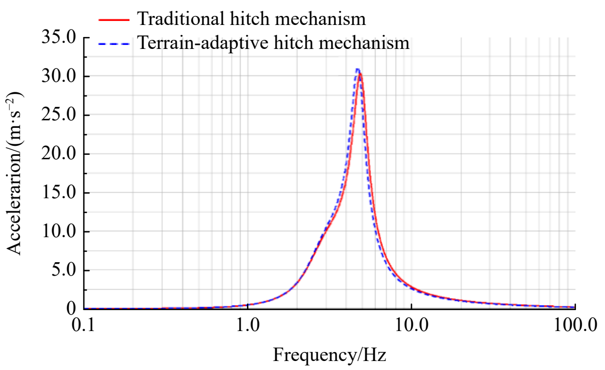


Figure 15 Frequency responses at centroid of driver

It can be seen from the figure that when using the traditional hitch mechanism, the vertical acceleration amplitude at the driver's centroid reaches the peak value of 30.4 m/s^2 at the frequency of 4.9 Hz, while when using the terrain-adaptive hitch mechanism, it reaches the peak value of 31.1 m/s^2 at the frequency of 4.7 Hz. Obviously, the new hitch mechanism will reduce the driver's resonance frequency by 0.2 Hz and increase the driver's acceleration amplitude by only 2.3%. This indicates that the use of the new hitch mechanism has little effect on the vibration characteristics of hilly tractors.

5.3 Fatigue analysis and structural optimization

As a bridge connecting the rotating bracket and rotating body, the rotating shaft is responsible for transferring soil resistance of farm implements to tractor body, and is the key force-bearing component of terrain-adaptive hitch mechanism. The structural strength of the rotating shaft, especially the fatigue strength, is vital to the safety of the whole mechanism. It can be seen from the Figure 14 that the load on the rotating shaft is relatively large, and its value varies greatly under different working slopes. Therefore, it is necessary to check the strength and optimize it after the preliminary structural design.

Structural design of the rotating shaft is calculated based on bending and torsion synthesis conditions in material mechanics. The rotating shaft belongs to the rotating mandrel, which is only subjected to bending moment but not torque. For hollow shafts, the design formula of shaft diameter is

$$d \geq \sqrt[3]{\frac{M}{0.1(1-\beta^4)[\sigma_{-1}]}} \tag{21}$$

where, d is the outer diameter of the shaft, m; M is bending moment on the shaft (N·m), $M=\sqrt{M_H^2+M_V^2}$; β is the ratio of inner diameter to outer diameter of the shaft, $\beta = d_1/d$, d_1 is the inner diameter of the shaft, m; and $[\sigma_{-1}]$ is the allowable stress under symmetrical cyclic alternating stress, MPa.

It is known that ADAMS simulation results are F_H= 7157.9 N, F_V= 6054.6 N. It is also known that the length of the force arm is l= 133.5 mm and the fatigue limit of Q235 steel is σ_{-1}= 176.3 MPa. The d≥49.6 mm can be calculated by Equation (21). In addition, the shaft length is 510 mm, which is determined by the assembly relations on the shaft.

In the Static Structure module of AYSYS Workbench, the geometric model of the rotating shaft is established and divided into a hexahedral mesh model with 4 mm mesh size, 198555 nodes and 47 242 elements. The parameters such as Young's modulus, Poisson's ratio, and S-N fatigue curve are set, and the material of the rotating shaft is defined as Q235 steel. Cylindrical constraint and axial displacement constraint are added at the front end of the rotating shaft to limit six degrees of freedom. The load applied to the rear end of the rotating shaft is decomposed into loads along x, y and z directions, and their values are negative 6302.3 N, positive 7157.9 N and negative 6054.6 N, respectively. Activate the Fatigue Tool module of ANSYS Workbench, and set the fatigue strength factor K_f as 0.9, the load type as symmetrical cyclic alternating stress, the amplitude scale factor as 1.2, and the analysis type as high cycle fatigue stress analysis. After automatic solution by the software, the distribution nephograms are obtained, as shown in Figure 16.

It can be seen from the figure that there is a phenomenon of stress concentration in the assembly gap between the rotating bracket and the rotating body. When the target fatigue life is 10^5 cycles, the maximum equivalent alternating stress is 32.1 MPa, which is much less than the fatigue limit of 138 MPa, and the fatigue safety factor is 4.3. This shows that the rotating shaft structure under this design is too safe.

From the point of view of energy saving and cost reduction, the strength reserve of the rotating shaft is too large and the material has not been fully utilized, so further structural optimization design should be considered. In this paper, the Response Surface Optimization module of ANSYS Workbench is employed to optimize the structure of the rotating shaft. The inner and outer diameters of the rotating shaft are taken as design variables, and the minimum mass of the rotating shaft is taken as the optimization objective. Constraints include boundary constraints and performance constraints. The boundary constraints are that the inner diameter meets 25 mm≤d_1≤35 mm, and the outer diameter meets 40 mm≤d≤50 mm. The performance constraints are that the fatigue safety factor is not less than 1.5, and the fatigue life is expected to reach 10^5 cycles.

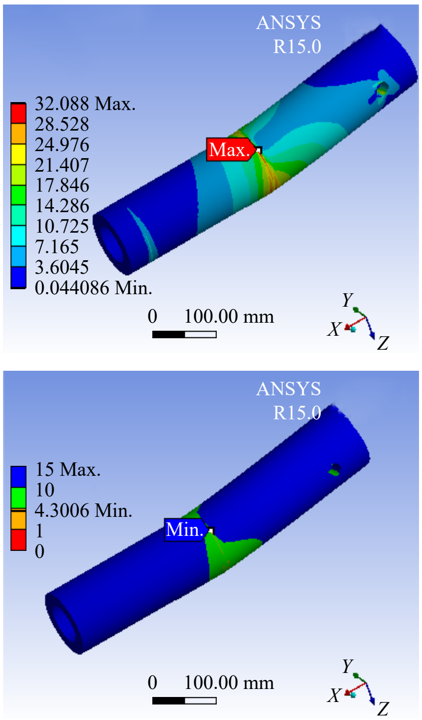


Figure 16 Distribution nephograms of equivalent stress and safety factor of rotating shaft

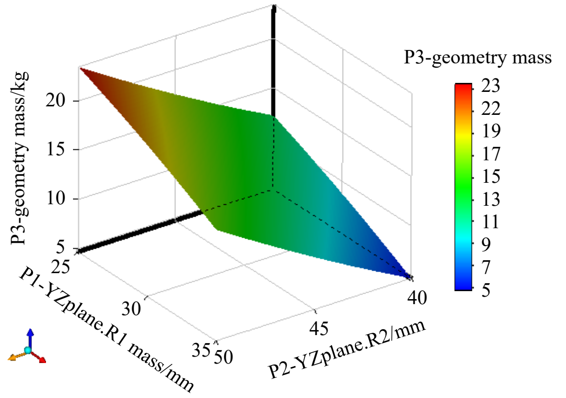
After the test design is completed, the software automatically fits the data to obtain the response surface of the inner and outer diameters and mass, and the response surface of the inner and outer diameters and fatigue life, as shown in Figure 17. According to the constructed proxy model, the system can perform optimization and obtain a series of candidate points. Select the best combination of design variables from the candidate points, then round the parameters, and finally update the geometric model and recalculate. Comparing the data before and after optimization, the results are shown in Table 6.

It can be seen from Table 6 that the inner diameter increases by 2 mm and the outer diameter decreases by 10 mm. The minimum fatigue safety factor is 1.59, and the minimum fatigue life is 9.58×10^5 cycles. The mass is reduced to 7.20 kg, with a reduction ratio as high as 64.0%. Through optimization design, the mass of the rotating shaft is effectively reduced on the premise of meeting fatigue strength and service life, so the lightweight design has been realized.

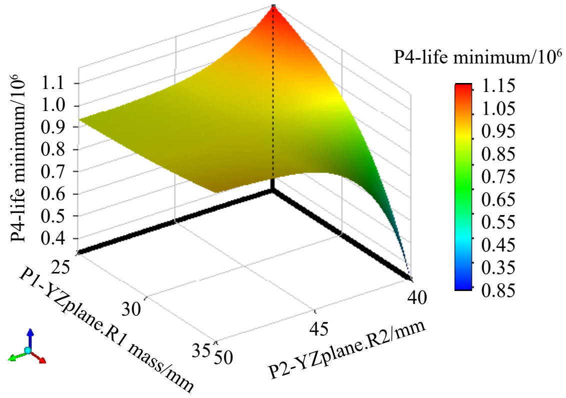
6 Experimental verification of terrain-adaptive hitch mechanism

6.1 Construction of test platform

Based on Wuzheng 40 horsepower tractor, a test platform is



a. Geometry mass



b. Minimum fatigue life

Figure 17 Mass and fatigue life response surfaces of rotating shaft

Table 6 Comparison of data before and after optimization of rotating shaft

Parameter	Inner diameter/ mm	External diameter/ mm	Mass/ kg	Minimum fatigue safety factor	Minimum fatigue life
Before optimization	30.00	50.00	20.02	4.30	≥ 10^6
After optimization	32.00	40.00	7.20	1.59	9.58×10^5

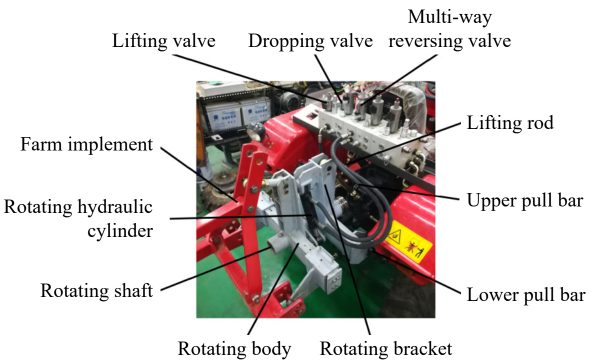
built to test the power lifting range and the working slope range of terrain-adaptive hitch mechanism.

The test platform of tractor rear hitch system is mainly composed of mechanical and hydraulic systems, virtual terminal and data acquisition systems, as shown in Figure 18. The mechanical system consists of a hitch device, a rotating device and a farm implement. The hydraulic system consists of a hydraulic pump, a multi-way reversing valve, a lifting hydraulic cylinder and a rotating hydraulic cylinder. The virtual terminal system is composed of a variable power supply, a controller, an inclination sensor and a display. The data acquisition system is composed of a USBCAN interface card and a notebook computer.

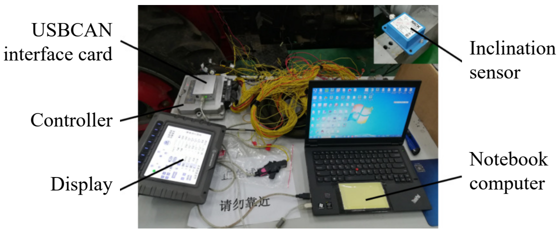
The rated flow of the hydraulic pump integrated inside tractor body is 20 L/min, and the rated pressure is 16 MPa. The transverse inclination angle of the farm implement is measured by the inclination sensor mounted on the rotating body. The inclination sensor is powered by 24 V power supply, and the output port of inclination signal is connected with the current acquisition port of controller AI21. The ground wire is connected with the analog ground port of controller AGND to form a loop, so that the controller can collect the inclination signal.

6.2 Test results and analysis

In the power lifting range test, there is no need to attach a farm implement. By controlling the lifting hydraulic cylinder to lift or drop terrain-adaptive hitch mechanism, the vertical distance from the lower hitch point to the ground is measured respectively when the lifting rod is adjusted to the shortest and longest situation. In the working slope range test, after programs are written into the controller, by clicking the adjustment button on the display, the controller outputs a specific current to control the action of the multi-way reversing valve, which makes the piston of the rotating hydraulic cylinder produce displacement, so as to realize the adjustment of transverse inclination of the farm implement. After the test is completed, save and process the data collected by USBCAN card on the computer. The tests of power lifting range and working slope range are shown in Figure 19. And the test results are shown in Table 7 and Figure 20, respectively.



a. Hydraulic and mechanical systems



b. Virtual terminal and data acquisition systems

Figure 18 Real vehicle test platform

Figure 19 Tests of power lifting range and working slope range

Table 7 Test results of power lifting range

Index	National standard/ mm	Theoretical value/ mm	Test value/ mm
Minimum height of lower hitch point	≤ 200	181	185
Transportation height of farm implement	≥ 820	833	857
Lifting stroke	≥ 610	652	672

It can be seen from the table that the actual power lifting range of terrain-adaptive hitch mechanism is 185-857 mm, which is basically consistent with the theoretical range of 181 mm to 833 mm. The maximum error of lifting stroke is 3.1%, which all meet the requirements of national standards. It can be seen from the figure that the maximum value of transverse inclination angle of the farm implement in negative direction is about 25.9°, and the maximum value in positive direction is about 23.2°, that is, the working slope of the farm implement is greater than 20°, which meets the design target. By further comparison with Figure 10, it is found that the actual working slope range of the farm implement is basically consistent with the theoretical range, with a maximum error of 4.5%.

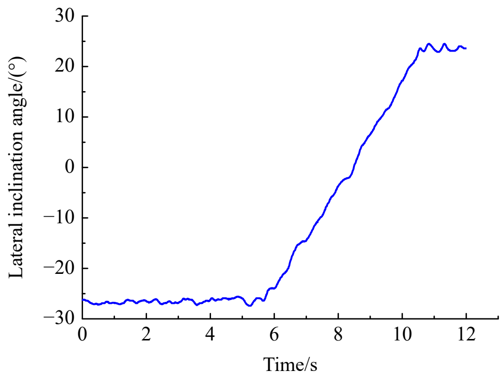


Figure 20 Test results of working slope range

7 Conclusions

1) Aiming at the problem that hilly tractors are difficult to adjust the transverse posture of farm implements, this paper designs a new type of terrain-adaptive hitch mechanism that can adjust the transverse posture of farm implements to no less than 20° for working on hillside fields.

2) The rotating device is the core of this novel terrain-adaptive hitch mechanism, which successfully realizes the copying operation function of farm implements. The addition of the rotating device does not impair the lifting performance of the original hitch device, and it scarcely affects the vibration characteristics of hilly tractors. These indicate that the migration performance of the new hitch mechanism is excellent and has good popularization value.

3) The modern design methods and processes adopted in this paper, such as theoretical analysis, simulation optimization and experimental verification, can complete the development of new products with high efficiency and high quality. It provides some reference for researchers in the agricultural machinery and equipment industry.

4) In the follow-up research, the cooperative control and optimization between the novel terrain-adaptive hitch mechanism and hilly tractors with body leveling system is the focus. This work may provide some help for the improvement of agricultural mechanization level and the development of agricultural economy in hilly and mountainous areas in the future.

Acknowledgements

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