DESIGN OF SMALL MULTIFUNCTION HYDRAULIC CHASSIS FOR HILLY REGIONS OF SOUTHWEST CHINA
/
西南丘陵山区小型多功能全液压底盘的设计

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Keywords: *small multifunction chassis, intercropping, crawler, hydraulic system, experiment*

ABSTRACT

A small multifunction hydraulic chassis was designed on the basis of the intercropping planting in the hilly regions of southwest China. The overall structure and the design parameters were completed by theoretical calculations and UGNX software. A track-based walking device was studied. It consists of a gauge of 720 mm and a minimum ground clearance of 200 mm. The prototype employs a full hydraulic drive system, effectively solving the steering problems in narrow spaces of intercropping fields. It can also navigate smoothly through a hilly intercropping field, is stable on slopes (<25°) and has good climbing ability.

摘要

针对西南丘陵山区地形及套作种植的特点，设计了小型多功能全液压底盘。通过理论计算及 UG 三维样机技术，完成了整机结构设计和关键部件参数的确定。本文主要研究了小型多功能底盘的行走装置，确定其为履带式，轨距为 720mm，最小离地间隙为 200mm；研究了全液压传动系统，此系统有效的解决了套作地头小空间转向问题，实现了原地 360° 转向。性能试验表明机器能够顺利通过丘陵套作田间作业，液压系统设计合理，动力足，能够平稳通过小于 25° 的斜坡，爬坡性能良好。

INTRODUCTION

The hilly southwest region of China (*Lv Xiaorong et al, 2011*) is a typical dry farming area. The region is remote and relatively inaccessible and its terrain is characterized by undulations and slopes, which makes it unsuitable to mechanized crop cultivation. Historically, intercropping has been the predominant method of cultivation in this region. This method involves planting crops in the spaces between narrow rows with intercropping spacing of 1m, where large-scale agricultural machinery cannot be operated. The intercropping pattern currently practiced in the hilly southwest region is that of "wheat/maize/beans." Its planting is basically a manual and artisanal process, with low productivity and high labour intensity (*Lv Xiaorong et al, 2011*). Hence, the development of miniaturized, lightweight and economical agricultural machinery that is suitable for use in hilly regions is of particular importance.

The "wheat/maize/beans" intercropping pattern employs strip crop rotation (*Lv Xiaorong et al, 2011; Vandeneer J.H., 1989; Fukai S. and Trenbath B.R., 1993; Fang Susu et al, 2017*). This method is implemented in a very narrow space. The undulating ground has a certain gradient and the soil is clayey. As such, the aim of the present study is to design a small multifunction chassis, which uses a self-propelled crawler, with a compact structure, small radius steering and high motor power. Various small-scale agricultural machines can be coupled to the chassis through the suspension support so that various operations such as tillage, seeding, fertilization, spraying of pesticides and irrigation can be carried out.

Most existing small-scale agricultural machinery employ wheel gears for movement. However, such machinery is not suited for use on the cohesive soil found in the southwest region (especially Sichuan). Operation of such machinery on slopes is difficult because of slipping. Moreover, the turning radius of wheeled machinery is large, which decreases manoeuvrability in narrow spaces (*Lv Xiaorong et al, 2011*). A track-based walking structure is proposed with a large ground-contact surface area, high traction, low subsidence and good steering. These features make it suitable for intercropping operations in the hilly region.

MATERIALS AND METHODS

- **Structure and operating principle of machinery**

Structure and Technical Parameters

The overall structure of the small multifunction chassis is shown in Fig. 1.

It consists of moving, control, hydraulic, suspension and transmission. The main technical parameters are listed in Table 1.

Table 1

Main technical parameters

No.	Item	Unit	Parameter
1	Dimensions	mm	2000 × 1100 ×1520
2	Structure weight	kg	540
3	Gauge	mm	720
4	Length of track in contact with the ground	mm	900
5	Minimum ground clearance	mm	200
6	Connection method		suspension
7	Maximum speed	km/h	5
8	Operating speed	km/h	1–2
9	Engine:		
	Rated power	kW	15
	Rated speed	(r/min)	3600
	Maximum torque	(N.m)/(r/min)	47/2600
10	Double pump:		
	Displacement	(CC/r)	12
	Maximum revolutions under idle load	rpm	3600
	System operating pressure	MPa	16

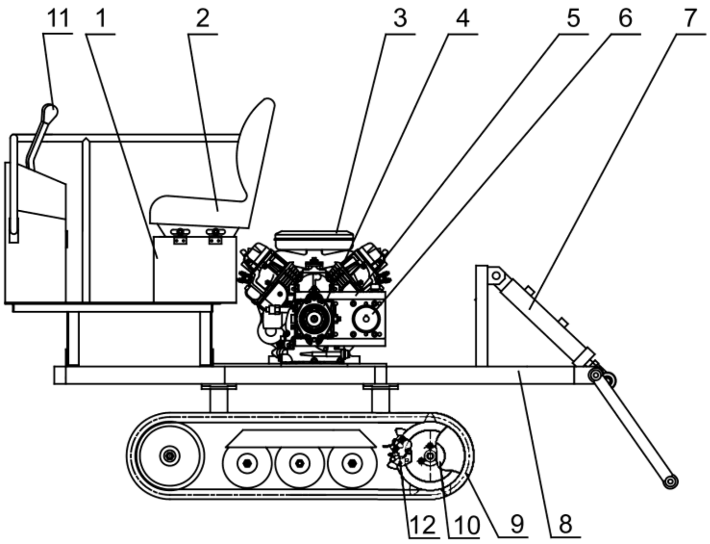


Fig. 1 - Overall structure shown in UGNX

1- Fuel tank; 2- Seat; 3- Engine; 4- Double pump; 5- Transfer case; 6- Gear pump; 7- Hydraulic cylinder; 8- Chassis; 9- Walking system; 10- Motor; 11- Operating system;12- Brake System

Operating Principle

During operation of the multifunction chassis, engine power is transmitted via the transfer case to the hydraulic system, which in turn transfers the power to the moving and suspension systems. This allows the chassis to carry out various moving operations, including forward, backward and turning movements. Planting, cultivation, and other farming operations can be carried out when the chassis is coupled to other agricultural machinery through articulation.

Structural Design of Moving System

The moving system of the proposed multifunction chassis comprises the track, driving, supporting, and steering wheels and the support frame. The left and right tracks wrap around the driving, supporting, and steering wheels and are in direct contact with the ground. The area of the track in contact with the ground is 900 mm long and 180 mm wide, and the gap between the two tracks is 720 mm. The operating principles are as follows: (i) the output power of the motor is transmitted to the driving wheels to drive the tracks; (ii) the steering wheels tighten the tracks, guide their motion, and absorb shocks; (iii) the supporting wheels transfer the entire weight of the machinery to the tracks. The wheels roll along the rails of the tracks to prevent lateral movement.

Determination of Main Parameters

In the design of the walking system, the important parameters include the track support length *L*, track gauge *B*, and width of the track shoe *b*. These must be reasonably matched so that the requirements for ground contact, adhesiveness and turning performance are met. We obtained the following empirical eq. from the agricultural machinery manual (****Agricultural Machinery Design Manual, 2007*):

$$L \approx 107\sqrt[3]{G} \tag{1}$$

$$\frac{L}{B} \approx 1.2 - 1.4 \tag{2}$$

$$\frac{b}{L} \approx 0.2 - 0.8 \tag{3}$$

Where：

L —Length of the supporting track, mm;

G—Initial operating weight of the machinery, kg;

B —Track gauge, mm;

b —Width of the track shoe, mm.

The initial weight of the crawler was G = 800 kg. Substituting this value into Formulas (1)–(3) gives:

$$L \approx 107\sqrt[3]{G} = 107\sqrt[3]{800} = 995 \text{ mm}$$

Where：

$L \approx$ 950 mm; B=613-750 mm; b=(0.18-0.22) L=162-198 mm

After comprehensive considerations, the length of the supporting track is 900 mm, the track gauge is 720 mm and the width of the track shoe is 180 mm.

Design of Full Hydraulic System

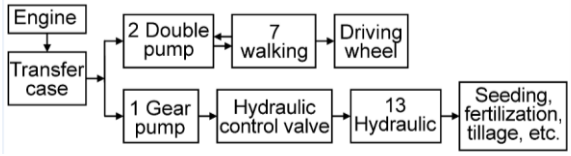
The chassis includes a complete hydraulic system and it differs from the existing agricultural steering technology, because it uses positive differential system for turning and a unilateral braking system. Here, bilateral reverse differential steering is introduced to micro- and small-scale agricultural machines for the first time. This technique facilitates pivotal turning of the machinery, and effectively reduces its steering radius and hence its weight.

- **OVERALL PROPOSAL**

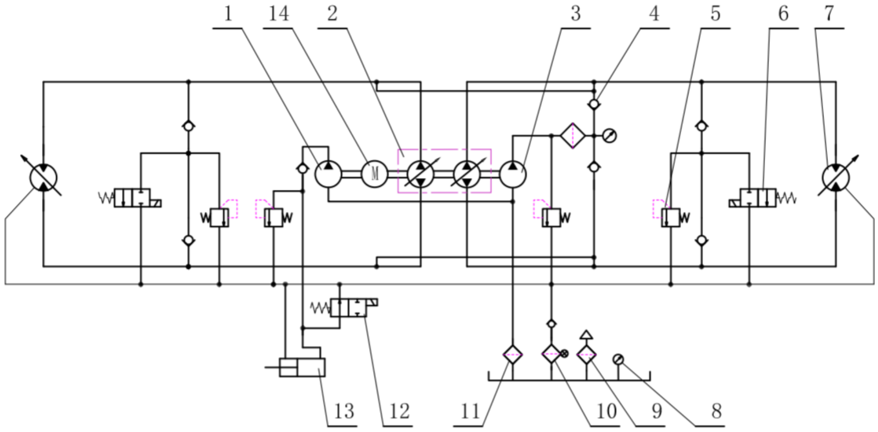
The hydraulic components of the multifunction chassis comprise a double pump and gear pumps, a driven motor and a hydraulic cylinder. The transmission and principle diagram of the hydraulic system is shown in Fig. 2.

The engine provides power to the double pump and gear pumps through the transfer case. The system is divided into two components. One supplies pressurized oil to the driven motor through the double pump. The dual-direction opening of the two joysticks for the double pump allows the driven motor to turn forward and backward and thus enables the chassis to move forward, move backward, turn, or stop. This results in two closed-loop hydraulic circuits.

The other component supplies pressurized oil through the hydraulic gear pump via an open-loop hydraulic circuit. It is controlled by manipulating a multi-way valve; it can lift and lower various operating systems, as well as operate various mechanical parts. Thus, the component enables seeding, fertilization, irrigation, and other farming operations to be carried out.



a)



b)

Fig. 2 - Hydraulic system of multifunction chassis
a) Schematic diagram of hydraulic system; b) Principle diagram of hydraulic system

1- Gear pump; 2- Double pump; 3-Charge pump; 4- Check valve; 5- Pressure relief valve; 6- Normally closed unloading valve; 7- Driven motor; 8- Gauge; 9- Air filter; 10- Return filter; 11-Suction filter; 12- Normally opened unloading valve; 13- Hydraulic cylinder；14- Electric engine

- **DETERMINING PARAMETERS OF MAIN HYDRAULIC COMPONENTS**

The main parameters for the design of a hydraulic system and selection of hydraulic components are the pressure and flow (6). The pressure is determined by the external load, whereas the flow in the hydraulic actuator is determined by the velocity of movement and the structural dimensions.

Selection of driven motor

The hydraulic motor converts hydraulic energy to kinetic energy so that the hydraulic actuator can rotate continuously. The motor torque is calculated as follows (*Merritt H.E., 1967*):

$$T_p = F_T \times r \tag{4}$$

$$\left.\begin{aligned} F_T &= F_q - F_f \\ F_q &\le F_\varphi \\ F_f &= f \times G_s \end{aligned}\right\} \Rightarrow F_T \le F_\varphi - fG_s \tag{5}$$

$$\left.\begin{aligned} F_\varphi &= \varphi G_\varphi \\ G_\varphi &= G_s \end{aligned}\right\} \Rightarrow F_\varphi = \varphi G_s \tag{6}$$

Where：

T_p - motor torque (N.m);
r - radius of the driving wheel of the track (mm);
F_T - traction force (N);
F_q - tangential driving force (N);
F_f - Rolling resistance (N);
F_φ - adhesion (N); G_φ - adhesion weight (kg);
G_s - weight used (taken as 800 kg);
f- rolling resistance coefficient (0.06–0.07);
φ - adhesion coefficient (0.9–1.1), from Eqs. (4)–(6).

The following is obtained:

$T_p \leq 1223.04 \approx 1223$ N.m

The displacement of the hydraulic motor is:

$$V_{gm} = (\frac{2 \times \pi \times T_g}{\Delta P}) / \eta_{mm} \leq 266.68\ ml/r \tag{7}$$

Where：

V_{gm} - motor displacement;

T_g - single motor torque ($T_p = 2 \times T_g$);

ΔP - pressure differential of motor ($\Delta P = 16 MPa$);

η_m - mechanical efficiency of motor (0.9–0.99).

The following were selected on the basis of theoretical calculations by considering the specific operational requirements: motor model M5-250; torque, 620 N·m; displacement, 250 ml/r.

Selection of double pump

This is mainly based on the maximum operating pressure and flow (*Merritt H.E., 1967*). The maximum operating pressure of the hydraulic pump *Pp* (Pa) of the multifunction chassis is calculated on the basis of the maximum operating pressure of the hydraulic actuator as follows:

$$p_p \geq p_1 + \sum \Delta p = 16.5 \text{ MPa} \tag{8}$$

Where：

p_p - Maximum operating pressure of the hydraulic pump;

p_1 - Maximum operating pressure of the hydraulic motor (16 MPa);

$\sum \Delta p$ - Total piping loss between the outlet of the hydraulic pump and the inlet of the hydraulic motor. A value in the range of 0.2–0.5 MPa was selected on the basis of empirical data.

The flow of the hydraulic pump is determined as follows:

$$q_{vp} \geq K\left(\sum q_{V\max}\right) \tag{9}$$

$$\sum q_{V\max} = \frac{V_{gm} \times n}{1000} = 23\ L/\min \tag{10}$$

Where：

q_{VP} - maximum flow rate of the hydraulic pump;

K - system leakage coefficient (usually in the range of 1.1–1.3);

$\sum q_{V\max}$ - Maximum flow of the hydraulic motor (L/min);

V_{gm} - Motor displacement (250 ml/r);

n -Shaft speed (89 r/min).

From Eqs. (9) and (10), q_{Vmax} is determined as ≥30 L/min.

OYP12 was selected as the model for the double pump. The maximum operating pressure and flow of the pump are 21 MPa and 33.6 L/min, respectively.

- **Design of speed measurement system**

The requirements for crop cultivation vary according to the conditions of the fields. In addition, for various reasons, crop density varies even within the same region. Real-time control and adjustment of the operating speed of the machinery are required.

In this paper, a rotary-driven testing system was designed to facilitate real-time control of the operating speed of the driving wheels. Data processing via a microcontroller is carried out to provide a good understanding of the multifunction chassis operating speed. The structure of the test system is shown in Fig. 3.

Inductive proximity switches (LJ24A3-10-Z/AX, Shanghai Hangrong electric Co., Ltd., Shanghai, China) are used to count wheel rotations. Each wheel has 11 teeth. The sine signal is converted to a square wave signal by using an optocoupler. The display circuit shows the speeds of the left and right wheels, which produce a periodic signal output for the pulse.

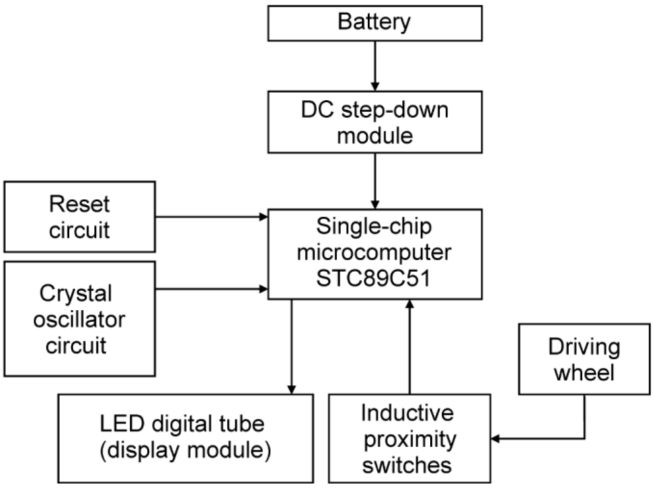


Fig. 3 - Rotary-driven speed test system

The relation between the frequency and pulse speed can be stated as follows:

$$n = \frac{f}{z} \times 60 \tag{11}$$

Where：

n—Speed of the driving wheel (r/min); f—Pulse frequency (Hz);

z—Teeth count of the driving wheel (min)

The real-time speeds of the left and right wheels are shown on the display and are adjusted using a control handle according to the actual operational requirements. With real-time monitoring and appropriate adjustments made to the driving speed of the machinery, operational speed is controlled.

- **Design and fabrication of three dimensional prototypes**

The UGNX6.0 three-dimensional software package was used to model and assemble the multifunction chassis as well as to detect the interference of machine components and the centroid of the machinery (*Ma Xinguo, Chen Yuanyuan, 2012; Jayaram S. et al, 1997; Deng Y. M. et al, 1991; Xiaorong Lüet et al, 2013)*. The results show that there is no interference between the various components. Therefore, the structural design of the machinery is acceptable. A prototype of the multifunction chassis was manufactured in Sichuan Agricultural University processing workshops.

- **PERFORMANCE TEST**

Test location

Performance tests of the multifunction chassis were conducted in November 2012 at the Sichuan Agricultural University (SAU) testing base and the nearby hilly region. The plots used for testing were intended for intercropping cultivation. The corn was ripe and had been harvested, leaving only the matured soybeans. Concrete pavements of various gradients (similar in condition to the many existing farm tracks in rural areas) are located in the hills behind the SAU. The steepest slope for pavements is approximately 31°.

RESULTS

Performance tests of the multifunction chassis were carried out in the hilly south-western region in accordance with the relevant provisions stated in Test Methods for Agricultural Wheeled and Crawler Tractors (*Snadu C et al, 2010; Huaifeng YANG et al, 2013; Liang Zhaoxin et al, 2012; Wen Aimin et al, 2014*). The testing criterion was the non-compaction of stems and leaves of the crops located on either side of the multifunction chassis when the machine passed through the intercropping band (Fig.4) at the Sichuan Agricultural University experimental field.

Fig. 4 - Performance testing on intercropping band

The multifunction chassis could smoothly navigate the narrow space within the intercropping band. There was no rolling of the crops on either side, demonstrating that the design parameters of the multifunction chassis could satisfactorily meet the requirements for intercropping cultivation in the hilly southwest region.

(2) Hills with different gradients, located behind the SAU, were also selected for testing (Fig. 5). The prototype was stationed on a straight road that is relatively flat. The machine was started at a slow speed and then accelerated at maximum throttle. It attained a stable speed by the time it reached the base of the slope for testing. It then climbed the slope at a steady speed. This test was performed thrice on each gradient. The test was considered a success if the machine was able to climb the slope at least once.

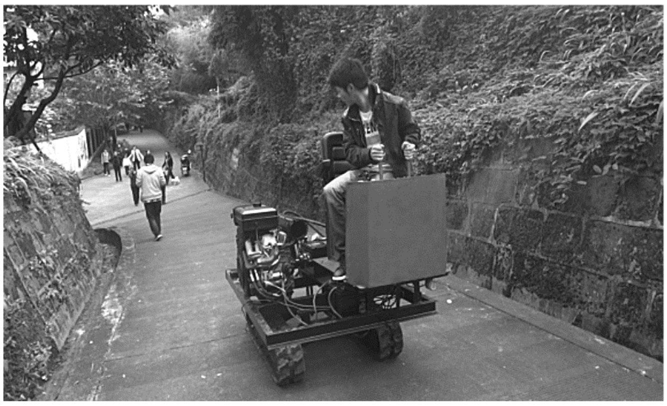


Fig.5 - Test of climbing abilities

During the climbing test, the driving speed for the multifunction chassis was 0.8 km/h. It could successfully climb a gradient with a maximum slope of 31°. The soil and water conservation law stipulates that “the limit of the slope for wasteland cultivation of crops should be <25° (*Nengye Liu, 2012*). The climbing capacity of the prototype is thus sufficient.

(3) The main purpose of steering the multifunction chassis was to observe its suitability for turning in narrow spaces. The turning tests involved observing/measuring bilateral forward and backward speed differentials, unilateral braking and turning radius.

The prototype displayed good steering ability. During a test of the bilateral backward speed differential, it achieved a 360° pivot turn.

CONCLUSIONS

The intercropping field tests, the multifunction chassis stability and smooth navigation through the ups and downs in the field, show that the chassis structure design is reasonable, with excellent traction and good stability performance, suitable for intercropping operations in the hilly region.

(1) The multifunction chassis could smoothly navigate the narrow space within the intercropping band. There was no rolling of the crops on either side, demonstrating that the design parameters such as caterpillar

track 720 mm, the width of 1100 mm and so on, could satisfactorily meet the requirements for intercropping cultivation in the hilly southwest region.

(2) During the turning test, the chassis achieved a 360° pivot turn, showing that design of hydraulic system achieves the function of reverse differential steering, thus solving the difficult problem of turning in narrow spaces.

(3) During the climbing test, the small multi-function chassis at 0.8 km/h speed, could smoothly pass a gradient of 31° slope degree, verifying that the chassis has good climbing abilities and is capable of steadily climbing a slope of <25°. The prototype thus meets the basic operational requirements stipulated for the use of agricultural machinery in the hilly regions of southwest China.

ACKNOWLEDGEMENT

The study was supported by the Key Laboratory of Modern Agricultural Equipment, Ministry of Agriculture, P.R. China (201602002), the National corn industry system project (CARS-02-29) and the National Natural Science Foundation of China (51105261).

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