SELF-DRIVEN STUBBLE CLEANING AND LAND PREPARATION COMBINED MACHINE, CHINA

自驱动灭茬联合整地机的设计与试验研究

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Abstract

In order to solve the problem consisting in the large amount of energy consuming of stubble-breaking cultivating machines, according to the current cultivation mode in the northeast China and the conservation tillage agriculture technical requirements, a self-driven stubble-breaking combined cultivating machine that can work with big-power tractors has been designed. Also, there were designed the transmission system, cutting stumbles device and self-driven wheel on the basis of calculating the size and analyzing the track of the moving parts; the speed range of stubble cutter shaft is 904~1365rad/min. Experiment results showed that the machine’s cutting stubbles rate is 92.30%, mashing clods rate is 95.03%, saved fuel consumption is about 25.3~33.8%, function and technology meet the requirements of corn no-till seeding of ridge culture area in northeast China. The results of the study have a great significance in reducing the agricultural equipment energy consumption, providing reference for the study of the corresponding high efficiency and energy saving of equipment.

Keywords: stubble-breaking cultivating machine; self-driven; design; test

Introduction

Conservation tillage technology has matured and has been gradually recognized worldwide. This technology has been widely used in China (LV R, et al., 2014), due to its advantages of environmental sustainability and increased grain production. A stubble cleaning and land preparation combined machine suitable for the specific national conditions of China is important to improve the domestic agricultural mechanization in the country (Kassam A. H. W. Li, et al., 2006).

Stubble cleaning and land preparation are important links in tillage conservation and are characterized by heavy work and large working resistance. Stubble cleaning and land preparation combined machines are vital to agricultural production and have been studied extensively. Internationally, Mouazen A M used a finite element method to analyze and optimize sub-soiling shovels (Mouazen A.M.; Neményi M. et al., 1999). W.C. Swick constructed a dynamic model of land tillage parts to predict the shear and friction stresses of working parts. Subrata Karmakar used the fluid dynamic (computational fluid dynamic) method to analyze stresses on land tillage parts during operation (Karmakar S. and Kushwaha R.L., et al., 2006). Domestically, Jia Honglei designed a rotary stubble cleaning and land preparation combined machine that is suitable for cultivation tillage (Swick W.C. et al., 1988; Jia H L. et al., 2007; Jia H L. et al., 2009). Tong Jin optimized the design of the rotary and stubble blades according to the theory of bionics (Jin T. et al., 2015). Sun Rongrong designed a stubble breaking device to prevent large soil disturbances (Sun R R., et al., 2008). Lin Jing designed the Archimedes spiral-type cap-cutting disc, which can effectively reduce stubble breaking resistance and improve ditching quality (Lin J, et al., 2014). These
studies focused on the design of deep-tillage parts and soil breaking parts, as well as the parameter optimization of stubble cutting and breaking devices. Consequently, the stubble breaking rate is improved. However, studies on energy conservation and consumption reduction methods to reduce the cost of agricultural production are scarce.

In this study, a self-driven stubble cleaning and land preparation combined machine (self-driven combined land preparation machine hereinafter) is presented. This machine can be used with a high-powered tractor. The rest of the paper is organized as follows. In the second part, the working principle of the proposed self-driven combined land preparation machine is clarified according to its technical requirements. The driving system, stubble cleaning device, and self-driven wheel designs are explained with theoretical analysis. In the third part, a prototype is produced and a field experiment is conducted to validate the design feasibility. The machine transforms the torque produced by friction between the self-driven wheels and the ground into the rotary driving force of the stubble cleaning blade axis. As a result, energy consumption is decreased effectively and the stubble cleaning and soil breaking rates are assured. Therefore, the machine achieves high performance efficiency and reduces cost.

MATERIAL AND METHOD

Overall design of the system

Stubble cleaning and land preparation combined machines can create good bed conditions for planting, improve the passing performance of the seeder, and ensure seeding quality. According to the working conditions and actual agronomic requirements, the technical requirements of the proposed stubble cleaning land preparation combined machine are as follows:

(1) This machine can reduce energy consumption during operation and reduce production cost effectively.

(2) This machine can complete root stubble crushing and soil breaking effectively. This machine can also meet the agronomic and conservation tillage technology requirements in the cold and ridge areas in Northeast China.

(3) This machine is mobile and has a complete machine structure with small vibration and consistent performance.

The entire structure of the self-driven combined land preparation machine is designed according to the basic parameters for completing stubble cleaning and proper land preparation. The main components of the machine are as follows: traction frame, walking wheels, stubble cleaning mechanism, transmission mechanism, gearboxes, and self-driven wheels (Fig.1). The transmission mechanism, stubble cleaning mechanism, and self-driven wheels are the main structures of the machine and are the main focus of this study.

Fig.1 - Self-driven Combined Land Preparation Machine
The self-driven combined preparation machine works under the traction of the hydraulic suspension system of the tractor. During operation, the torque caused by friction between the self-driven wheels and the ground drives the self-driven axis to rotate, and the power is transmitted to the stubble cleaning device through the chain drive, gearbox, and belt drive. The stubble cleaning device thus accomplishes stubble cleaning and soil breaking. The driving pawl of the self-driven wheels is embedded into the ground, which can also accomplish some stubble cleaning work. The working depth can be adjusted by the depth-limited cylinder. The driving force needed by the self-driven combined land preparation machine is no longer provided by the tractor, but transformed from the torque generated by friction. This phenomenon reduces the power output of the tractor and energy consumption. The main performance indicators and technical parameters of the machine are shown in Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
<th>Item</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>(L×W×H) / (mm×mm×mm)</td>
<td>Diameter of Stubble Cleaning Blade Axis (mm)</td>
<td>8000×5570×1300</td>
</tr>
<tr>
<td>Working Width (mm)</td>
<td>4400</td>
<td>Rotation Speed of Stubble Cleaning Blade (rad/min)</td>
<td>904~1365</td>
</tr>
<tr>
<td>Operation Speed (km/h)</td>
<td>8~12</td>
<td>Stubble Cleaning Depth (mm)</td>
<td>720</td>
</tr>
<tr>
<td>Traction Power (kW)</td>
<td>180~220</td>
<td>Stubble Cleaning Rate (%)</td>
<td>92.30</td>
</tr>
<tr>
<td>Diameter of Self-driven Wheel (mm)</td>
<td>1075</td>
<td>Soil Breaking Rate (%)</td>
<td>95.03</td>
</tr>
</tbody>
</table>

**Design of the driving system**

The tillage power of the self-driven combined land preparation machine is generated by the rotation of driving wheels. The rotation speed of these wheels is limited by the walking speed of the machine. A speed change device must be installed to satisfy the required rotation speed transmitted to the stubble cleaning shaft, thereby satisfying the agricultural technical requirements of straw returning.

The drive system design requires rational allocation at all levels to meet the rotation speed requirement and ensure the minimum size of the overall drive system. The design scheme is shown in Fig. 2. The machine has a biaxial structure. The self-driven wheels in the self-driven area rotate because of friction with the ground. The rotation speed increases through the chain drive, secondary gearbox, and belt drive, and then is transmitted to the stubble cleaning shaft in the stubble cleaning area where stubble cleaning work is accomplished. The two-gearbox structure can ensure the stability and reliability of power transmission.

![Fig.2 - Drive System Design Scheme](image)

The feed speed of land preparation machines commonly used in the three provinces of Northeast China is 8 km/h to 12 km/h, and the common rotation speed of the stubble cleaning shaft ranges from 1000 r/min to 1500 r/min. The diameter of the self-driven wheel disc is Ф800 mm. Using Formulas (1) and (2), the range of the drive ratio $i$ of the drive mechanism is 12.5≤$i$≤18.86.

$$i = \frac{V}{n}$$

(1)

$$i = \frac{V_m}{n}$$

(2)

Where $n$ is the rotation speed of the self-driven pawl (r/min), $V$ is the edge linear speed of the self-driven fixed pulley (m/min), $V_m$ is the general rotation speed of the stubble cleaning shaft, 1000 (r/min), $i$ is the drive ratio.

After the calculation, the drive ratio of chain drive $i_{ch} = \frac{L_1}{L_2} = 1.58$

the primary drive ratio of the straight gear $i_{43} = \frac{Z_2}{Z_4} = 3$

the secondary drive ratio of the straight gear $i_{56} = \frac{Z_5}{Z_6} = 2$

the belt drive ratio $i_{ab} = \frac{L_1}{L_2} = 1.8$

The teeth number of gears at different levels and diameters of the chain and belt wheels of the drive system can be determined by referring to the mechanical design manual in Table 2.

<table>
<thead>
<tr>
<th>Drive Ratio of the Drive System and Size Parameters of Driving Parts</th>
<th>Drive Ratio $i$</th>
<th>Teeth Number of Large/Small Gear</th>
<th>Reference Diameter of Large/Small Chain Wheel (mm)</th>
<th>Diameter of Large/Small Belt Wheel (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain Drive</td>
<td>1.58</td>
<td>27/17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gearbox Tier 1</td>
<td>3</td>
<td>-</td>
<td>386/128</td>
<td>-</td>
</tr>
<tr>
<td>Gearbox Tier 2</td>
<td>2</td>
<td>-</td>
<td>244/122</td>
<td>-</td>
</tr>
<tr>
<td>Belt Drive</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
<td>180/100</td>
</tr>
</tbody>
</table>

The rotation speeds of the stubble cleaning blade axis at two running speeds are calculated as:

$$n_{\text{min}} = n_{\text{min}} \times (i_{12} \times i_{34} \times i_{56} \times i_{ab}) \approx 904\text{r/min}$$

$$n_{\text{max}} = n_{\text{max}} \times (i_{12} \times i_{34} \times i_{56} \times i_{ab}) \approx 1365\text{r/min}$$

The calculations show that, when the proposed self-driven combined land preparation machine runs at the speed of 8~12 km/h, the rotation speed of the stubble blade axis ranges from 904 rad/min to 1365 rad/min. This range is in accordance with the requirement of a common speed range for combined land preparation machines. Thus, the drive mechanism design is reasonable. The drive system is shown in Fig.3.

Fig.3 - Drive System of the Self-driven Combined Land Preparation Machine
Design of the Stubble Cleaning Device

To reduce the soil damage caused by the tillage process, the seeding process is conducted on the surface of the earth covered by crop straw and stubble. The no-till seeding machinery in China is behind that in foreign countries in terms of anti-blocking technology, and the seeding process has high seedbed requirements. Specifically, stubble in the land must be cleaned before seeding. The stubble cleaning device is an important part of the proposed self-driven combined land preparation machine. This device can break the roots and clods in soil and improve the passing performance and seeding quality of the seeder. It can also loosen the soil, maintain moisture, and improve the soil aggregate structure.

According to the movement mechanism of the self-driven stubble cleaning device, the stubble blade can move in two ways: one is the running of the entire machine at a certain speed \( v_m \), and the other is the circular rotary motion of the blade around the blade axis at a certain linear velocity \( v_0 \). Thus, the vector equation of absolute velocity is established as

\[
\mathbf{v} = \mathbf{v}_m + \mathbf{v}_0
\]

Using the center of the blade axis \( O \) as the origin point, a rectangular coordinate system is established with the forward direction of the machine as the positive half of the x-axis, and the upward direction perpendicular to the earth as the positive half of the y-axis (Fig. 4). The motion trajectory equation of the blade endpoint \( N(x,y) \) is obtained by

\[
\begin{align*}
x &= v_n t + R \cos \omega t \\
y &= R \sin \omega t
\end{align*}
\]

where \( \omega \) is the angle speed of the blade axis (rad/s), \( v_n \) is the forward speed of the machine, \( R \) is the radius of gyration of the stubble cleaning blade (m).

![Fig.4 - Motion Trajectory Diagram of the Endpoint of the Blade](image)

The ratio of the circular speed of the stubble cleaning blade to the moving speed of the machine is defined as the stubble cleaning ratio expressed by \( \lambda \):

\[
\lambda = \frac{v_n}{v_m} = \frac{R \omega}{v_m}
\]

The endpoint of the stubble cleaning blade is denoted as \( N \). When \( \lambda > 1 \), the motion trajectory of \( N \) is trochoidal (Fig. 5). The trajectory in a period of motion is investigated. The maximum and minimum horizontal distances on the trajectory line are set as \( A, B, \) and \( C \). When the blade moves to the BC section, the horizontal velocity of the absolute motion of the stubble cleaning blade endpoint is opposite the moving direction of the self-driven stubble cleaning device. In this case, the edge of the blade can cut the soil and stubble and throw them backward to achieve stubble cleaning and land preparation. To facilitate the rotary cutting function of the stubble cleaning blade and break the clods on the surface and the root stubble under the ground, \( \lambda > 1 \) in the design.

![Fig.5 - Trochoidal Motion Trajectory of N](image)
A straight blade is used as the stubble cleaning blade (Fig. 6). The size parameters of this blade are shown in Table 3. The straight blade is characterized by good soil cutting, breaking, and throwing properties. This blade is also widely used because of its simple manufacturing requirements. The stubble cleaning blade must have high wear resistance because it needs to contact the soil and reach into it. Accordingly, the stubble cleaning blade of 65 Mn is used in the design (Zhang X Y et al., 2009).

![Fig. 6 - Straight Blade Stubble Cleaner](image1)

### Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indentation Angle</td>
<td>119°</td>
<td>Bending Radius</td>
<td>40 mm</td>
</tr>
<tr>
<td>Diameter of the Blade Axis</td>
<td>580 mm</td>
<td>Blade Angle</td>
<td>17°</td>
</tr>
<tr>
<td>Blade Thickness</td>
<td>1.5 mm</td>
<td>Cutting Width</td>
<td>150 mm</td>
</tr>
</tbody>
</table>

The structure of the stubble cleaning blade axis is determined on the basis of the motion analysis results and size of the stubble cleaning blade (Shentu L F. et al., 2007). The main components of this blade axis are as follows: joint tray, stubble cleaning blade, blade disc, fastening device, blade axis, bearing, and belt wheel (Fig.7). A total of seven stubble cleaning blade discs are present on the blade axis. Each blade disc has a diameter of 350 mm and a rotation angle of 12.8°. Four straight blade stubble cleaners are fastened by bolts on each disc; two on the left and two on the right are fastened in alternating and symmetrical positions (Jia H L. et al., 2011; Tu J P. et al., 2003). The width and depth of the stubble cleaning device are 4400 and 72 mm, respectively. The rotation speed of the stubble cleaning blade axis is 904 rad/min to 1365 rad/min. The stubble cleaning device is shown in Fig. 8.

![Fig.7 - Structure of the Stubble Cleaning Blade Axis](image2)

![Fig.8 - Stubble Cleaning Device of the Self-driven Combined Land Preparation Machine](image3)
Design of Self-driven Wheels

During operation, the pawls on the self-driven wheels are embedded into the soil. The self-driven shaft rotates because of the soil resistance force, and the power generated is transmitted to the stubble cleaning assembly through the drive mechanism. Stubble cleaning and soil breaking are completed in the roll cutting operation.

The main components of the self-driven wheels are as follows: chain wheel, self-driven wheel pawl, self-driven wheel disc, self-driven shaft, fastening device, joint tray, and bearing (Fig. 9). Nine self-driven wheel discs alternate on the self-driven shaft, which can enhance the uniformity and stability of the device. The diameter of the self-driven wheel disc is set to 800 mm for the purpose of increasing the self-driven moment arm and improving the power conversion rate.

![Fig. 9 - Structure Display of the Self-driven Wheel](image)


The self-driven wheels function as the power input part of the self-driven system, and the edge of each wheel is hollow. The fixed part of the self-driven pawl is embedded in the self-driven wheel and fastened through welding and fastening device to ensure the fastening strength. The parameters of the self-driven wheels are shown in Table 4, and the real object is shown in Fig. 10.

![Fig. 10 - Self-driven Wheels of the Self-driven Combined Land Preparation Machine](image)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>1040x100</td>
<td>Number of Pawls</td>
<td>16</td>
</tr>
<tr>
<td>Wheel Disc Diameter (mm)</td>
<td>800</td>
<td>Angle of Pawl (°)</td>
<td>22.5</td>
</tr>
<tr>
<td>Space between Wheels (mm)</td>
<td>245</td>
<td>Number of Wheels Discs</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4 - Main Parameters of Self-driven Wheels
RESULTS

Field Experiment

The experiment was conducted in Team 2 corn stubble field of Jianshe Farm in Heilongjiang Province, during May 12 and May 26, 2013. No treatment was performed before the experiment. The experimental tools mainly included the proposed self-driven combined land preparation machine (Fig. 11), a Deer7820 tractor (equipped with GPS), a platform scale (accurate to 0.1 kg), a soil moisture measuring instrument, a soil density measuring instrument, a set of oil measuring devices, and two rulers. The physical parameters of the soil in the experimental field are shown in Table 5.

![Self-driven Combined Land Preparation Machine](image)

**Table 5**

<table>
<thead>
<tr>
<th>Parameters of the Experimental Field</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation Amount (kg/m³)</td>
<td>2.0</td>
</tr>
<tr>
<td>Soil Density (KPa)</td>
<td>36.5</td>
</tr>
<tr>
<td>Absolute Moisture Content in Soil (%)</td>
<td>19.8</td>
</tr>
<tr>
<td>Corn Stubble Height (cm)</td>
<td>15–36</td>
</tr>
</tbody>
</table>

**Stubble Rate Measurement**

In accordance with the industrial standards of the rotary tiller combined work machine (JB/T8401.2-2007), the measurement and calculation method of the stubble cleaning rate is as follows: select several points in the corn stubble field according to a specific schedule and write the number as n; mark a 1 m² area at each point to measure the root stubble in the scope; stubble shorter than or equal to 5 qualifies (Ma H L, et al., 2007); substitute the data into Formula 4 to calculate the stubble cleaning rate:

\[ P = \frac{M_h}{M_g} \times 100\% \]  

(4)

where \( P \) is the stubble cleaning rate of the \( n^{th} \) plot (%), \( M_h \) is the weight of the stubble shorter than 5 cm in the \( n^{th} \) plot (Kg), \( M_g \) is the total weight of the stubble in the \( n^{th} \) plot (Kg).

**Soil Breaking Rate Measurement**

The calibration method of the soil breaking rate is similar to that of the stubble cleaning rate. The measurement and calculation method is as follows: select several points in the corn stubble field according to a specific schedule and write the number as n; mark an area of 0.5 m × 0.5 m at each point to measure the weight of clods with the longest edge of shorter than 4 cm and are within 10 cm under the ground and the total weight of all clods; substitute the data into Formula 5 to calculate the soil breaking rate:

\[ E = \frac{M_a}{M_b} \times 100\% \]  

(5)

where \( E \) is the soil breaking rate of the tillage layer within 10 cm under the ground in the \( n^{th} \) plot (%), \( M_a \) is the total weight of the clods shorter than 4 cm within 10 cm under the ground in the \( n^{th} \) plot (Kg), \( M_b \) is the total weight of the clods within 10 cm under the ground in the \( n^{th} \) plot (Kg).
**Oil Consumption Measurement**

The starting and ending lines were marked before the experiment. A preparation area was set aside. The tractor pulled the self-driven combined land preparation machine to enter the detection area at a constant speed. When the front end of the machine touched the starting line, the oil measurement device was activated. When the back end of the machine touched the ending line, the measurement ended (Guo Z J. et al., 2003). In the experiment, the speed, width, time, and working conditions were measured by the GPS on the tractor and the data were recorded. Oil consumption was calculated according to Formulas (6) and (7) (Fang Z.H. et al., 2000).

\[
K = \frac{G}{W} \quad (6)
\]

\[
W = 0.1BV \quad (7)
\]

where \( K \) is the oil consumption amount (kg/hm²), \( G \) is the oil consumption of the machine per hour (kg/h), \( W \) is the productivity of the machine (hm²/h), \( B \) is the working width (m), \( V \) is the operation speed of the machine (km/h).

**Experimental Results**

In the experiment, the tractor pulled the self-driven combined land preparation machine at a constant speed of 10 km/h for four land preparation cycles. Afterward, the parameters were measured and recorded and the means were calculated. The results are shown in Table 6.

<table>
<thead>
<tr>
<th>Operation Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>Mean</td>
</tr>
</tbody>
</table>

The results show the field environment has 36.5 KPa soil density, 19.8% moisture content, and 15~36 cm deep corn root stubble. The self-driven combined land preparation machine completes the stubble cleaning at 10 km/h and achieves a stubble cleaning rate of 92.30% and a soil breaking rate of 95.03%. The average oil consumption of the commonly used combined land preparation machines, such as Ecolo-Tiger 730C and John Deere 2700, is between 21.0L and 18.6L per hectare. Meanwhile, the oil conservation rate of the machine in this study is 25.3%~33.8%.

**CONCLUSIONS**

In this study, a self-driven combined land preparation machine is designed to overcome the large power consumption of the commonly used stubble cleaning and land preparation combined machines. The design of key parts of the proposed self-driven combined land preparation machine is discussed in detail. The main conclusions of this study are as follows. The alternating and symmetrical arrangement of the stubble cleaning blades improves the stubble cleaning effect and the stress of the stubble blade axis, and ensures the running stability of the machine. The increase in the diameter of the self-driven wheel disc increases the force provided to the self-driven arm, thereby obtaining superior driving effect. However, in terms of the counterweight of the entire machine, smaller diameter of self-driven wheel disc translates to better performance. The simulation analysis shows that a diameter of 800 mm provides optimal performance. With the increase in the running speed, the stubble cleaning blade axis rotates faster, thereby improving the rates of stubble cleaning and soil breaking. However, in high-speed operation, the load of the stubble cleaning blade increases and thus can result in its damage. Furthermore, overly high speeds may reduce the land preparation effect. The optimal speed for the combined land preparation machine is 10 m/s. These conclusions provide a reference for designing similar self-driven combined land preparation machine and shortening the development cycle. However, the practical production shows that, when the land humidity is high, the self-driven wheel pawls cannot be embedded in the soil firmly. As a result, the self-driven effect reduces and no effective driving force is provided. Therefore, the design of self-driven wheels must be optimized further, particularly the structure and arrangement of self-driven wheel pawls.
ACKNOWLEDGEMENT
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