Design of an Efficiently Operated Digging Tillage Machine for Small Tea Farms

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***Abstract* — an efficiently operated digging tillage machine is designed for small tea farms and focused to avoid the problems of repeated tillage and plough leakage. Firstly, the prototype of small tea farm plough tillage machine is designed based on knowledge of manual operation and relevant information. Then, an installation scheme for efficient operation is presented by simulating the motion trajectory of plough tillage mechanism. Secondly, speed ratio equation for plough tillage mechanism and driving wheel is deduced based on the constraints of repeated tillage, plough leakage and decelerated box power transmission ratio formula. Thirdly, eight sets of data about the theoretical deep tillage and plough distance are processed by the least squares curve fitting to obtain the best fitting curve. The equation relating speed ratio and planning depth is then determined. Finally, an improved design scheme is proposed after prototype verification based on the above equations. The research results can avoid repeated tillage and plough leakage to improve the operation efficiency.**

Keywords - small tea farm; repeated and leak tillage; plough; the least squares; curve fitting; efficient operation

I. Introduction

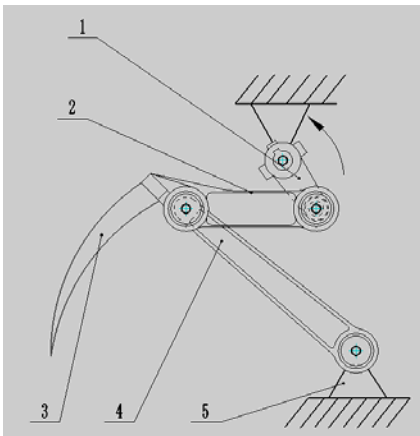
Tea garden farming is one of the most important work in tea garden management, which can be divided into shallow tillage, cultivation and deep plowing [1]. Meanwhile, tea garden cultivation has been the research focus in recent years, which is advantageously characterized by weeds cleaning, soil physical properties improving, the tillage layer curing and so on[2,3]. Currently, there are various cultivation machineries, such as the vertical rotary tillage, horizontal rotary tillage, prying type tillage, plough etc[4,5]. However, repeated tillage and leak tillage are still the obvious problems in the process of operation, resulting in poor operation effect, low work efficiency, and high energy consumption. The source of the problems lies that the machine design mostly depends on experience and. lacks of theory supports. Therefore, it is of importance to research about the tea garden farming machine from the theoretical view and provide the theory basis.

In the next section, the operation principle of the prototype of small tea farm digging tillage machine is firstly presented. Secondly, optimal installation of digging tillage mechanism is determined by simulating motion trajectory of the agency. Thirdly, a mathematical model is proposed based on the related design manual and data. In section 3, the experiment for the prototype of small tea garden digging machine is carried out in Jiangsu tea-bo-garden. Then, the least square curve fitting method is applied fit the relation between the digging distance and tilling depth. Next the best optimal fitting curve is achieved. According to the mathematical model obtained in section 2, the relationship between tilling depth and rotation rate of driving wheel and digging mechanism can be eventually converted for further explanation. In section 4, the model is utilized to analyze the optimal rotation rate for the prototype. Finally, research conclusions are summarized.

II. Small tea garden digging tillage machine

A. *Operation principle)*

Tea garden digging tillage techniques originated from human action, and the principle for the small tea garden digging tillage machine is designed based on crank and rocker mechanism [6]. Crank, connecting rod and rocker are connected by hinge. The crank rotates to drive the connecting rod and the rocker swing. Meanwhile, the digging tillage tools are installation through a locking bolt in the connecting rods. Then, the target for tea garden cultivation can be achieved when the digging tillage tools work with motion of cranks, connecting rods and rockers. The principle illustration is shown in Figure1.



1—cranks；2—connecting rods；3—digging tillage tools；4—rokers；5—frame

Fig.1. The tea garden digging tillage mechanism schematic diagram.

B. *Installation of digging tillage mechanism*

According to Fig.1, nose of digging tillage tool can reach the longest distance when the crank and connecting rod run in a straight line without coincide. In this paper, the optimal installation position can be confirmed when nose of digging tillage tool reach the longest distance, which is illustrated as shown in Fig.2.

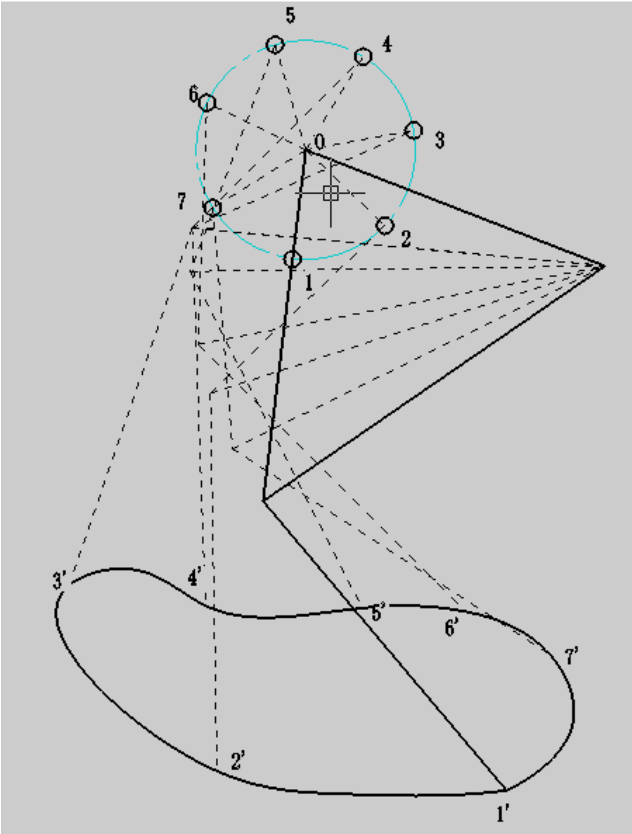


Figure 2. Simulation trajectory schematic diagram for nose of digging tillage tool

According to Fig.2, nose of digging tillage tool moving trajectory is simulated by 7 points, among which, the position of point 1 is the optimal installation of the mechanism. In such a situation, the connecting distance from center O on the crank to point 1' on the digging tool is the longest. Then, the efficient operation of the prototype can be obtained when the longest connecting distance is perpendicular to the earth. Thus, the optimal installation position can be finally confirmed.

C. *Mathematical model of the constraint to avoid repeated and leak tillage*

1) preliminary design of the deceleration box

According to Fig.1,the driving power of cranks originate from the output shaft of the decelerated box, which is the core of the prototype, and designed based on relevant data and design experience. The design principle for decelerated box from small tea garden digging tillage prototype made in Wuxi worldbest KAMA power co.,ltd, China, is illustrated as shown in Fig.3.

1—the power input wheel; 2—the power input shaft; 3—the driving gear; 4—the driven gear; 5—the transition shaft 1; 6—the driving gear; 7—the driven gear; 8—the transition shaft 2; 9—the driving gear; 10—the driven gear; 11—the output shaft 1; 12—the driven gear; 13—the transition shaft 3; 14—the driving gear; 15—the driven gear; 16—the driving gear; 17—the output shaft 2; 18—the driven gear; 19—the driving shaft; 20—chassis

Figure 3. The decelerated box transition diagram

As Fig.3 shown, the decelerated box involves six groups of gears, seven transition shaft, one power input shaft, three transition shafts and three power output shafts. Among them, the output shaft 1is the power source of the digging tillage crank rocker mechanism, the output shaft 2 is the backup power shaft, and the driving shaft drives the driving wheel operating. In addition, the gears between output shaft 1 and transition shaft 3, which is a growth portfolio, are designed to save space and provide space for the fork clutch operation. The parameters design of transition gears between output shaft 1 and driving shaft is constrained by the need for driving wheel speed and output shaft 1 speed in order to avoid repeated and leak tillage.

According to mechanical design manual, the transmission ratio can be described as $i_{j,j+1} = \omega_j / \omega_{j+1} = z_{j+1} / z_j$, where i stands for transmission ratio, ω for gear angular velocity, and z for the number of gear teeth. In addition, $\omega = 2\pi n$,where *n* stands for speed of revolution. Gear transmission ratio can be converted to $i_{j,j+1} = \omega_j / \omega_{j+1} = n_j / n_{j+1}$. Then,

$$i_{17} = i_{12} i_{2'3} i_{3'4} i_{45} i_{5'6} i_{6'7} = \frac{z_2}{z_1}\frac{z_3}{z_{2'}}\frac{z_4}{z_{3'}}\frac{z_5}{z_4}\frac{z_6}{z_{5'}}\frac{z_7}{z_{6'}} = \frac{n_1}{n_2}\frac{n_2}{n_3}\frac{n_3}{n_4}\frac{n_4}{n_5}\frac{n_5}{n_6}\frac{n_6}{n_7} = \frac{n_1}{n_7} \quad (1)$$

2) Establishment of mathematical model

The constraint of avoiding repeated and leak tillage is that the moving distance of machine while the digging tillage mechanism turn around should be equal to the digging distance in the heading direction. Thus, four formula will be introduced into the establishment of mathematical model, which can avoid repeated and leak tillage. They

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are $v = 2\pi R / T$, $T = \frac{1}{n_7}$, $t = \frac{1}{n_4}$, $s_j = vt$, among which, s_j stands for the digging distance in the heading direction of machine, v for the velocity of machine, R for the driving wheel radius, T for the time consuming per a circle of driving wheel, n_7 for the driving shaft rotational speed, t for the time consuming per a circle of output shaft 1, and n_4 for rotational speed of the output shaft1.

Thus, the expression for avoiding repeated and leak tillage can be simplified as

$$s_j = vt = 2\pi R \frac{n_7}{n_4} \qquad (2)$$

The transmission relationship between the driving shaft and output shaft 1 can be concluded based on formula as :

$$i_{47} = i_{45} i_{5'6} i_{6'7} = \frac{n_4}{n_5} \frac{n_5}{n_6} \frac{n_6}{n_7} = \frac{n_4}{n_7} \qquad (3)$$

Then, $s_j = vt = 2\pi R \frac{n_7}{n_4} = 2\pi R / i_{47}$ (4)

According to formula (4), s_j also is related with digging depth denoted by h. Therefore, the relationship between s_j and h will be the next research through test and the least square curve fitting.

III. TEST ON SMALL TEA GARDEN DIGGING TILLAGE PROTOTYPE

On November 30, 2014, field tests for the small tea garden digging tillage prototype which can be shown in Fig.4 was carried out in Jiangsu tea-bo-farm. The natural conditions for experimental field which meet the experiment need can be detected as soil firmness 17.92kg/cm2, and soil moisture content 16.13% in the depth between 0 to 10 cm, 31.93% in the depth between 10 to 20 cm and 23.21% in the depth between 20 to 30 cm.

Figure 4. Small tea garden digging tillage prototype

The test will be carried out in the condition of variable digging depth. Meanwhile how to change the digging depth can be illustrated as shown in Fig.5.

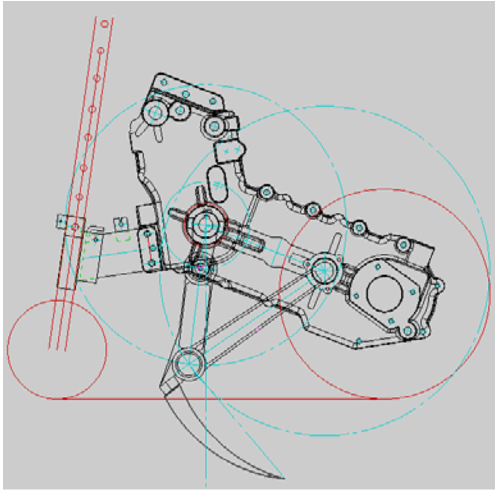

Figure 5. Schematic diagram of assembled prototype

According to Fig.5, the digging depth can be changed through adjusting the installation position between the guide rod mounting hole and body frame. There are eight installation holes in the guide rod. The eight installation position is shown in Figure.5 and the eight theoretical digging depth can be calculated with eight different installation position. And then the actual digging depth and digging distance will also be measured as listed in Tab.1 in the eight different installation positions. The data achieved by average treatment are listed below.

TABLE 1 THE CALCULATED AND MEASURED DATA IN EIGHT DIFFERENT INSTALLATION POSITIONS

Installation position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Theoretical digging depth h (mm)	20	33	44	58	75	95	116	140
Actual digging depth h_1 (mm)	22	35	48	60	80	105	120	135
Digging distance s (mm)	95	120	148	180	241	280	310	330

A. The error analysis of theoretical and actual digging depth

According to Table1, the error analysis of theoretical and actual digging depth can be sorted as listed in Tab.2.

As Table 2 shows, the biggest error of theoretical and actual digging depth is 10.5%, the main two reasons lie in the rough land and extrusion pressure between soil and digging tool, where the rough land changed the buried depth of digging tool and the extrusion pressure results that actual digging depth is deeper than theoretical digging depth. Among them, the actual digging depth is lower than theoretical digging depth in the eighth installation position, which is resulted in the rough land.

TABLE 2. ERROR ANALYSIS OF THEORETICAL AND ACTUAL DIGGING DEPTH

Installation position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Theoretical digging depth h (mm)	20	33	44	58	75	95	116	140
Actual digging depth h_1 (mm)	22	35	48	60	80	105	120	135
Error $\frac{\lvert h_1 - h \rvert}{h}$	10 %	6%	9.1 %	3.4 %	6.7 %	10.5 %	3.4%	3.6%

B. Relationship of actual digging depth and distance

According to Tab.1 and formula (4), the digging distance increases with the increase of actual digging depth. It is of importance to research the relationship between ‘s’ and ‘h’. The least squares curve fitting method will be introduced with Matlab to analyze the relationship between ‘s’ and ‘h’[7]. The polynomial fitting model can be shown as $s = a_0 h^0 + a_1 h + \cdots + a_n h^n$, and the polynomial coefficients as $a_0, a_1, \cdots a_n$,are calculated by the least square method. By tool Matlab[8], it is found that more than 4th degree polynomial fitting curve is serious distortion. Therefore, less than 5th degree polynomial fitting curve will be considered, whose residual error σ^2 for 4 groups of polynomial can be listed in Tab.3.

TABLE 3 THE RESIDUAL ERROR FOR 4 GROUPS OF POLYNOMIAL

N	**1**	**2**	**3**	**4**
Residual error σ^2	41.77	22.935	12.95	9.4492

As Tab.3 shows, the 4th degree polynomial residual error is 9.4492, which sands for the best fitting result. And the best fitting curve can be shown in Fig.6.

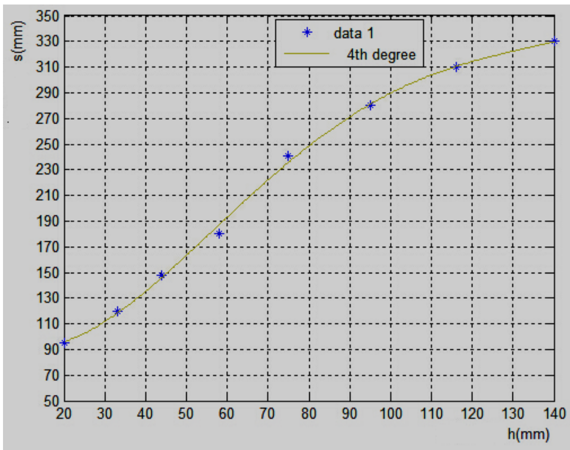

Figure 6. The optimal fitting curve between ‘s’ and ‘h’

According to Fig.6, the curve fitting can favorably show the relationship between ‘s’ and ‘h’. thus 4-degree polynomial can be selected as the final result. The specific curve equation can be calculated by Matlab as follows:

$$s = 2.4952 \times 10^{-6} h^4 - 0.00094426 h^3 + 0.11195 h^2 - 2.4184 h + 106.78$$

$$(20<h<140) \tag{5}$$

C. The final mathematical model between i_{47} and h

According formula (5) and formula (4), the final mathematical model between i_{47} and h which can avoid the repeated and leak tillage is shown as:

$$i_{47} = 2\pi R / (2.4952 \times 10^{-6} h^4 - 0.0009442 h^3 + 0.11195 h^2 - 2.4184 h + 106.78)$$

$$(20<h<140) \tag{6}$$

IV. CASE STUDY AND VERIFICATION

A. Verification for the best farming conditions of the designed prototype

According to formula (4), $s = \dfrac{2\pi R}{i_{47}}$.

The specific design process of the reduction box will not be introduced, while , according to Fig.3, the gear wheel design parameters of the reduction box will be listed as follows;

$z_1 = 15$; $z_2 = 21$; $z_{2'} = 14$; $z_3 = 25$; $z_{3'} = 19$; $z_4 = 47$; $z_5 = 45$; $z_{5'} = 21$; $z_6 = 50$; $z_{6'} = 27$; $z_7 = 51$.

According to formula (1) and (3),

$$i_{47} = i_{45} i_{5'6} i_{6'7} = \frac{z_5}{z_4} \frac{z_6}{z_{5'}} \frac{z_7}{z_{6'}} = \frac{45}{47} \frac{50}{21} \frac{51}{27} \approx 4.3,$$

among them, The radius of driving wheel is R=160mm. Then,

$$s = \frac{2\pi R}{i_{47}} = \frac{2\pi \times 160}{4.3} \approx 234mm.$$

According to formula (5), the theoretical digging depth is $h = 74.36mm$, which can avoid repeated and leak tillage. And as Tab.1 shows, the relationship table of theoretical digging depth and actual digging distance can be shown as Tab.4.

TABLE 4 THE RELATIONSHIP TABLE OF THEORETICAL DIGGING DEPTH AND ACTUAL DIGGING DISTANCE

Installation position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Theoretical digging depth h (mm)	20	33	44	58	75	95	116	140
Digging distance s (mm)	95	120	148	180	241	280	310	330

As Tab.4 shows, with the optimal digging distance $s = \frac{2\pi R}{i_{47}} = \frac{2\pi \times 160}{4.3} \approx 234mm$, it will not be adopt because of the arisen leak tillage phenomenon in the installation position from 1 to 4; While it will be analyzed as shown in Tab.5 because of the arisen repeated tillage phenomenon in the installation position from 5 to 8.

TABLE 5 THE REPEATED TILLAGE ERROR IN THE CONDITION OF INSTALLATION POSITION FROM 5 TO 8

Installation position	**5**	**6**	**7**	**8**
Theoretical digging depth h (mm)	75	95	116	140
Digging distance s (mm)	241	280	310	330
The best result for prototype s_z (mm)	234			
Repeated tillage error $\frac{s_j - s_z}{s_z}$	3%	19.7 %	32.5 %	41%

As Tab.5 shows, the repeated tillage error increased with the increase of installation position from 5 to 8. The theoretical digging tillage is close to the best tillage in the condition of installation position 5th, where the error is 3%. And the working efficiency is reduced greatly and the fuel consumption is increased in the condition of installation position 8th., where the repeated tillage error is 41%. Therefore the prototype design parameters should be improved in the next part.

B. Improved design proposal

The designed prototype belongs to the cultivating operation machine, whose digging depth can range from 100 to 150 cm. Thus, it is feasible to repeatedly design the prototype based on the installation position mentioned above, and then the prototype will be improved through choosing the biggest theoretical digging depth h=140mm. Considering the main requirements of environment and efficient operation, the mechanical design experts in the field of tea garden set the allowed repeated tillage error as 10% after some discussion. According to repeated tillage error formula in Tab.5 and formula (5), get $s_z = 300mm, h_z \approx 107mm$. Then the optimal digging depth range from 107 to 140mm. In the condition of not considering the ranged driving wheel radius, get $i_{47} = \frac{2\pi R}{s_z} = 3.35$. Thus it stands for the improved transmission ratio between output shaft 1and driving shaft, which provides the design base for transmission shaft and gear parameters in reduction box.

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V. CONCLUSION

1) According to power transmission formula about reduction box, the rotation ratio equation between output shaft 1 in the digging tillage mechanism and driving shaft in the driving wheel of the prototype is deduced.

2) By test of the prototype, the theoretical digging depth , actual digging depth and digging distance are obtained. As Table 2 shows, the biggest error of theoretical and actual digging depth is 10.5%, the main two reasons lie in the rough land and extrusion pressure between soil and digging tool, where the rough land changed the buried depth of digging tool and the extrusion pressure results that actual digging depth is deeper than theoretical digging depth. Among them, the actual digging depth is lower than theoretical digging depth in the eighth installation position, which is resulted in the rough land.

3) The 4-degree polynomial fitting curve is the optimal fitting curve, and the optimal fitting curve equation is achieved through the residual analysis based on the least squares curve fitting method.

4) According to the rotation ratio mentioned above and the optimal fitting curve equation, the mathematical model which can avoid repeated and leak tillage is finally achieved.

5) According to the final mathematical model, the prototype optimal operating depth is verified with h=74.3mm, which is beyond the allowed range from 100 to 150 mm of cultivator. Therefore, the prototype should be

improved. Considering the main requirements of environment and efficient operation, the mechanical design experts in the field of tea garden set the allowed repeated tillage error as 10% after some discussion. According to repeated tillage error formula in Tab.5 and formula (5), get $s_z = 300mm, h_z \approx 107mm$. Then the optimal digging depth range from 107 to 140mm. In the condition of not considering the ranged driving wheel radius, get,

$$i_{47} = \frac{2\pi R}{s_z} = 3.35$$
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Thus it stand for the improved transmission ratio between output shaft one and driving shaft, which provides the design base for transmission shaft and gear parameters in reduction box.

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REFERENCES

[1] Xiao Hongru,Mei Song,Song Zhiyu,Ding Wenqin,Han Yu. “Research on comprehensive performance evaluation of cultivation machinery for tea garden”, Applied mathematics & Information sciences, vol. 8, No. 5, pp. 2537-2543,2014.

[2] Hui W, Ren-Kou X U, Ning W, et al. “Soil acidification of alfisols as influenced by tea cultivation in Eastern China”,Pedosphere, vol. 20, No. 6, pp. 799-806, 2010.

[3] Yuan D, Yang D, Pu G, et al. “Fertility dynamics of three types of tea garden soils in Western Sichuan, China”,Pak. J. Agri. Sci, vol. 50, No. 1, pp. 29-35,2013.

[4] Feng Z U O. “Research and promotion of small tea plantation farming machinery”, Hunan Agricultural Machinery, vol.39, No.1, pp.28-29,2012.

[5] Yang L L, Tang X Y, Shi J, et al. “Status and development trends of Pu'er tea industrial mechanization and automation”,Advanced Materials Research. 756, pp. 4681-4684,2013.

[6] Brodell R J, Soni A H. “Design of the crank-rocker mechanism with unit time ratio”,Journal of Mechanisms, vol. 5, No. 1, pp. 1-4,1970.

[7] Van Huffel, Sabine, and Philippe Lemmerling, eds. “Total least squares and errors-in-variables modeling: analysis, algorithms and applications”,Springer Science & Business Media, 2013.

[8] Lv Ximing,Li Mingyuan.“The Realization of Curve Fitting with Matlab”,Journal of Inner Mongolia University for Nationalities (Natural Sciences), vol. 24, No. 2, pp. 126-127,2009.