OPTIMAL DESIGN OF THE SURFACE OF THE HIGH-SPEED REVERSIBLE PLOW / 高速翻转犁犁体曲面优化设计

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ABSTRACT

The farmland in Xinjiang of China is mainly sandy loam soil, on which the crops are subject to flat planting with mulched film. Before planting, the soil should go through deep ploughing in a short operation period, thus there is high demand on the high-speed plow and it is necessary to optimize the plow based on tillage resistivity to improve its working performance. In view of optimal design of the surface of high-speed reversible plow, simulation test was adopted to optimize the resistivity model, then finite element method was used to test the force condition of the plow. At last, the tillage resistivity of the plow after optimization was tested by soil bin test. Test results showed that, at tilling depth of 300 mm, tilling speed of 12 km/hm, and when the plow height was 250 mm with cutting angle of 37° and dozer angle of 84°, the plow achieved the optimal tillage resistivity and the optimal combination was 2.85 N/cm^2; at tilling depth of 300 mm, soil moisture content of 17%, and soil compactness of 220 N/cm^2, the maximum tensile stress on the surface of the plow was 115.61 MPa and total deformation was 2.869 mm; the maximum flexible strain of the plow was 9.38×10^{-4}. Soil bin test showed that, at tilling depth of 300 mm, dozer angle of 84°, the optimized high-speed reversible plow reduced the tillage resistance by 17.9% compared with common high-speed reversible plow made in China, and can provide reference to the design of high-horsepower tractors.

摘要

新疆农田以沙壤土为主，农作物采用覆膜平作方式，播前土壤均需要深耕作业，作业周期短，对高速犁体有较大需求，需要针对耕作比阻进行高速犁体优化，以提升国产犁的作业性能。本文针对高速翻转犁犁体曲面优化设计问题，采用仿真试验方法优化犁体比阻模型，利用有限元方法验证犁体受力情况，最后，通过土槽试验测试优化后犁体的耕作比阻。结果表明：当耕深深度为 300mm，耕作速度为 12km/h，犁体高度为 250mm，起土角为 37°，推土角为 84°，犁体具有最佳的耕作比阻，最优组合为 2.85 N/cm^2；在作业深度为 300mm，土壤含水率为 17%，土壤坚实度为 220N/cm^2,犁体曲面所受最大拉应力为 115.61Mpa，犁体总变形为 2.869mm，犁体最大弹性应变为 9.38×10^{-4}；土槽试验结果也表明，当作业深度为 300mm，耕作速度为 12km/h，犁体高度为 250mm，起土角为 37°，推土角为 84°，优化后的高速翻转犁犁体比普通国产高速翻转犁犁体的耕作阻力低 17.9%，优化后的高速翻转犁犁体可为国产大马力拖拉机犁提供设计参考。

INTRODUCTION

Plow body is the main working component of reversible plow in high-speed working, and the parameter optimization of plow surface (*Yang & Yang, 2003*) directly affects tillage quality and traction resistance and affects the working speed of plow. Experts in China and abroad have carried out a great deal of studies on the optimization design of plow surface (*Hou, 1981*). *A. Ibrahmi et al. (2015)* studied the surface of plow body and did force analysis on the plow bottom by computer by taking Bezier surface as the basic construction model; *Mouazen et al. (2010)* did simulation analysis on the performance of moldboard plow. *Zhao & Mei (2010)* did simulation analysis on the surface of high-speed plow body; Gan, Sun, & Cheng (2008) developed 1FFSL-5 type reversible plow to realize shallow ploughing and deep digging in tillage. *He et al. (2016)* designed a 1LF-550 grille type hydraulic overturn and amplitude modulation plow, which has simple structure and results in low resistance and avoids soil blocking.

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The surface of the plow is a complicated multi-space geometric surface (*Lin et al., 2016*), thus it is difficult to study the characteristics of the surface based on digital soil bin laboratory and field tests. The farmland in Xinjiang of China is mainly sandy loam soil, and plants such as cotton are subject to flat planting with mulched film. Before planting, the soil should go through deep ploughing in a short operation period, thus high-powered high-speed plow should be chosen in tillage. At present, plow body made by developed countries such as Reken (*Hu et al., 2020*) and Gregoire Besson were mainly adopted in Xinjiang for high horsepower tractors, and the agricultural machinery market in China lacks such advanced plows. Besides, the plows developed in other countries are not specially designed according to the soil conditions in Xinjiang, so totally optimized plow body has not been adopted in high-speed operation and thus it is not suitable for the plow operation in Xinjiang. It is of great significance to design a kind of high-speed plow suitable for farmland in Xinjiang and optimize the structural parameters and improve the working performance of the plow body of high horsepower tractors.

By taking the plow body of high-speed reversible plow as the object of study, resistivity parameters of the plow were adopted for orthogonal test, then the significance of force factors of the plow were analyzed by MATLAB and the optimal parameter values of different factors were obtained to analyze the force condition of the plow under specific soil humidity, compactness and adhesive force. Then the plow surface model was drawn by Solidworks, and simulation analysis was done on the plow surface by ANSYS, and the stress distribution diagram of the plow surface was established to analyze the shape variation of the surface and the influence of different factors on traction resistance, at last, the plow was designed to reduce the specific resistance of the plow body tillage and increase the plow body tillage speed.

MATERIALS AND METHODS

Optimization model of the plow surface

The main factors affecting the tillage resistivity of the plow include dozer angle, cutting angle, soil covering angle and plow height. It has been proved that the tillage resistivity of the plow is closely associated with parameters such as plow height, soil covering angle, cutting angle and dozer angle, and the equation of tillage resistivity is:

$$F_T = C_0 + C_1 x_1 + C_2 x_2^2 + C_3 x_1 x_2 + C_4 x_2 x_3 + C_5 x_2 + C_6 x_3 \quad (1)$$

where F_T is tillage resistivity; x_1 is cutting angle; x_2 is dozer angle; x_3 is plow height; and $C_0, C_1, C_2, C_3, C_4, C_5, C_6$ are constants.

By taking the tillage resistivity on the plow during stable tillage operation as test index, and plow height A, soil covering angle B, cutting angle C, dozer angle D were taken as test factors, the software Solidworks was used for modeling and the model was imported into ANSYS for four-factor three-level orthogonal test (Zhang et al., 2019; Li & Hu, 2005). Without considering the interaction, the ANSYS simulation experiment analysis was carried out. In the simulation test, the tillage speed was 12 km/h and the tillage depth was 300 mm. According to theoretical analysis, the variation ranges of the four factors were: plow height in 200-240 mm, soil covering angle in 55°-750°, cutting angle in 30°-36°, dozer angle in 74°-90°; the test was repeated three times to calculate test errors. The factors and levels of the orthogonal test are shown in Table 1, and test result analysis is shown in Table 2.

Table 1

Factors and levels of the orthogonal test

Level	Plow height [mm]	Soil covering angle [°]	Cutting angle [°]	Dozer angle [°]
1	240	75	36	90
2	220	65	33	82
3	200	55	30	74

Table 2

Test result analysis

Test No.	A	B	C	D	Tillage resistivity ($N \cdot cm^{-2}$)
1	1	1	1	1	0.90
2	2	2	2	1	0.84

Table 2
(continuation)

Test No.	A	B	C	D	Tillage resistivity ($N \cdot cm^{-2}$)
3	3	3	3	1	0.82
4	3	2	1	2	0.73
5	1	3	2	2	0.92
6	2	1	3	2	0.89
7	2	3	1	3	0.85
8	3	1	2	3	0.76
9	1	2	3	3	0.94
K_1	2.79	2.57	2.51	2.56	
K_2	2.59	2.54	2.54	2.84	
K_3	2.32	2.61	2.65	2.88	
k_1	0.93	0.86	0.84	0.85	
k_2	0.86	0.85	0.86	0.95	
k_3	0.77	0.88	0.90	0.96	
Range Rj	0.16	0.03	0.04	0.11	
Influence order of factors	A>D>C>B				
Optimal level	A_3	B_2	C_1	D_1	
Optimal combination	$A_3D_1C_1$ B_2				

It can be seen from the range analysis in Table 2 that, the influence order of factors is A, D, C, B, and the optimal combination is $A_3B_2C_1D_1$. Since the soil covering angle had the slightest influence on tillage resistivity, in order to simplify analysis, soil covering angle can be ignored, in this way, the relationship between plow height A, cutting angle C and dozer angle D with tillage resistivity should only be considered. Therefore, the following regression equation can be established:

$$y = 1.43704 + 0.08332x_1 + 0.00007x_2^2 - 0.00113x_1x_2 + 0.00049x_2x_3 + 0.01391x_2 + 0.00344x_3 \quad (2)$$

where, x_1 is cutting angle, x_2 is dozer angle and x_3 is plow height.

The software origin was used to establish the regression equation, and results showed that the significance level was 95%, showing great significance. The regression equation of tillage resistivity is shown in Table 3.

Table 3

Results of coefficients of regression equation

Tillage resistance	b6	b5	b4	b3	b2	b1	b0
Regression coefficient	0.00344	0.01391	0.00049	-0.00113	0.00007	0.08332	1.43704

Establishment of the target function

Taking the tillage resistivity of the high-speed reversible plow as the object of study, and the design variables being: plow height, cutting angle and dozer angle, then the regression equation was established after simulation analysis and the objective function was obtained.

The design variable $X=[x_1,x_2,x_3]^T$=[cutting angle, dozer angle, plow height]^T

$Minf(x)=y=1.43704+0.08332x_1+0.00007x_2^2-0.00113x_1x_2+0.00049x_2x_3+0.01391x_2+0.00344x_3$

Constraint conditions

Plow height: $g6(x)=200-x_3 \leq 0$; $g5(x)=x_3-240 \leq 0$.

Dozer angle: $g4(x)=74°-x_2 \leq 0$; $g3(x)=x_2-90° \leq 0$.

Cutting angle: $g1(x)=x_1-36° \leq 0$; $g2(x)=30°-x_1 \leq 0$.

Mathematical model of the tillage resistivity of the plow

$Minf(x)=y=1.43704+0.08332x_1+0.00007x_2^2-0.00113x_1x_2+0.00049x_2x_3+0.01391x_2+0.00344x_3$

$X=[x_1,x_2,x_3]^T$

s.t.gm(x)=0(m=1,2,3……6)

Advantages of the tillage resistivity of the plow

The edited codes are imported into the code editor of MATLAB and:

Function f=fun(x)

$F(x)=y=1.43704+0.08332x_1+0.00007x_2^2-0.00113x_1x_2+0.00049x_2x_3+0.01391x_2+0.00344x_3$

The edited codes are saved into the fun.m text, and the MATLAB software was used to solve the optimal combination of tillage resistivity, and:

```
1b=[30;75;25];
ub=[37;84;20];
x0=[33;83;27]
 [x,fn]=fmincon(@fun,x,[],[],[],[],1b,ub}
fprintf(1,`f=%3.4f\n`,fn)
fprintf(1,`x3=%3.4f\n`,x(3))
fprintf(1,`x2=%3.4f\n`,x(2))
fprintf(1,`x1=%3.4f\n`,x(1))
```

And the optimal solution is: X_3=20.0000; X_2=84.0000; X_1=37.0000; f=2.85KPa。

Results showed that, when limit depth was 300 mm, tillage speed was 12 km/h, plow height was 250 mm, cutting angle was 37°, dozer angle was 84°, the plow had optimal tillage resistivity, which was 2.85N·cm-2. It can be obtained after comparing with the analysis table that, the optimized tillage resistivity was reduced by 22.7% at most, and 8.96% at least.

Design of the plow surface

Lead curve graphing

In order to reduce the resistivity of the high-speed reversible plow, taking the high-speed reversible plow, made in China, as an example, and by referring to the plow surface design method in the Agricultural Machinery Design Manual (*Chinese Academy of Agricultural Mechanization Sciences, 2007*) and the conclusion drawn in section 2 of this paper, the maximum designed tilling depth was 300 mm, the maximum cutting angle was 37°, the maximum dozer angle was 84°, the maximum plow height was 250 mm, and the maximum tillage speed was 12 km/h. Lead curve is the guide line to determine the location of the horizontal straight line, and lead curve in the shape of parabola is mainly used in the design of plow surface. In this paper, according to tilling depth, the straight-line segment length S was determined to be 45 mm, and the parabola part of the lead curve was drawn based on the envelop method (*He, He, & Yang, 2019; Zhou et al., 2019*), as shown in Fig.1.

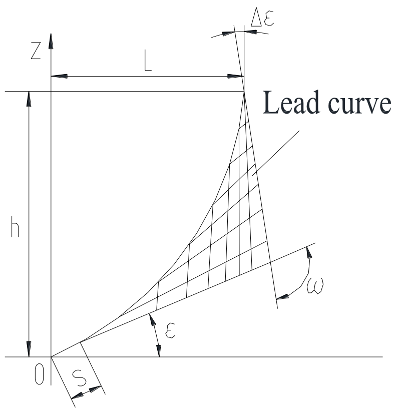


Fig. 1 - Lead curve

$$L=C_7b(\cos\Delta\varepsilon - \sin\varepsilon) \quad (3)$$

$$h=l\left(\frac{\cos\varepsilon+\sin\Delta\varepsilon}{\cos\Delta\varepsilon - \sin\epsilon}\right) \quad (4)$$

$$\omega=\frac{\pi}{2}+\varepsilon - \Delta\varepsilon \quad (5)$$

where: L is the openness degree;

C_7 is a constant;

b is width;

$\Delta\varepsilon$ is the buckling angle of the lead curve;

ε is the installation angle of the plow blade;

h is the height of the lead curve;

ω is the angularity of tangent line of the end point. In order to improve the ground-breaking efficiency of the plow, reduce the tillage resistivity, improve the tillage speed and reduce tillage wastage,

ε was determined to be 37°.

C_7 is a constant, generally in the range of 1.0-1.7. If smaller value is taken, the soil crushing effect would be enhanced, however, the soil turning effect is reduced with higher resistance.

In order to ensure the tillage quality, C_7=1.2.

Establishment of a 3D model

The software SOLIDWORKS was used to establish a 3D model of the plow surface. First, a reference datum was chosen to draw the sketch for plough blade line and the lead curve, then the "boundary-surface" command was used to generate a smooth surface, and finally a 3D model of the plow surface is finished, as shown in Fig. 2.

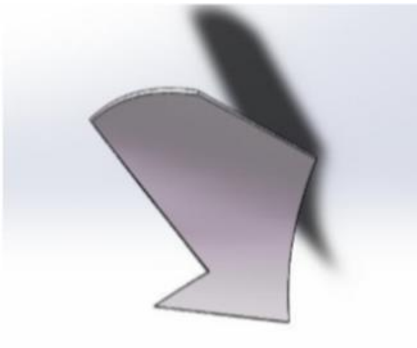


Fig. 2 - 3D model of the plow

Finite element modeling

The 3D model of the plow surface drawn in SOLIDWORKS was converted into x-t format, and imported into the ANSYS workbench platform for finite element static analysis. In ANSYS software, the material property of the plow body was determined to be carbon steel and the material property was rigid body, as shown in Fig 2. In analysis, the range of tillage speed was set to be 10-12 km/h, and limit depth was 300 mm, and on this basis, the force analysis was carried out on the plow surface. Then mesh generation was carried out to generate 6129 quadrilateral meshes with 13365 mesh points, as shown in Fig. 3; then a load of 2572 N was applied to the surface of the plow body, as shown in Fig. 4.

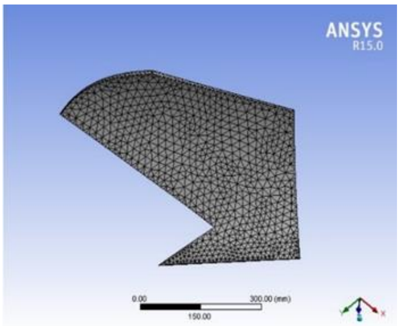


Fig. 3 - Mesh generation diagram

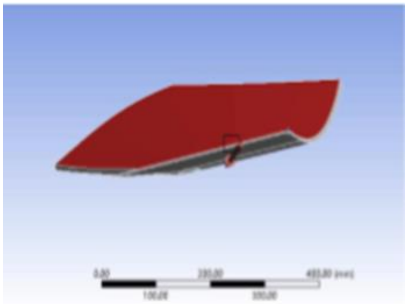


Fig. 4 - Load application to the plow body

Static characteristics analysis of the plow body

The plow body model was solved by the Block Lanczos method in ANSYS software by modal analysis. The Block Lanczos method has high calculation accuracy and requires short convergence time. According to (*Sun, Liu, & Yang, 2020; Zhao et al., 2019*), the low-order modal may have a relatively large impact on the vibration of the system, and only the first few natural frequencies and modal shape cloud nephograms are required.

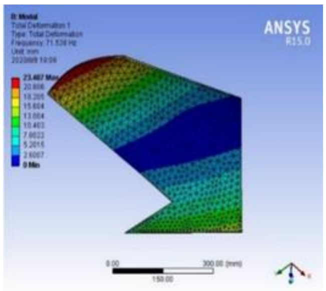
The modal diagrams of each order of the plow body were solved by ANSYS software, the natural frequencies of the first 6-order plow body are shown in Table 4.

Table 4

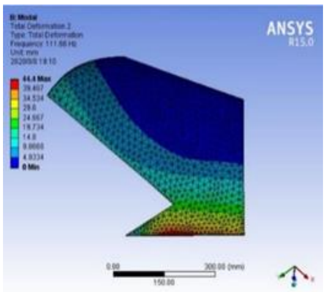
Natural frequencies of first 1-6 orders of the plow body

Orders	Natural frequency (Hz)
1	71.54
2	111.66
3	167.80
4	237.52
5	341.59
6	374.06

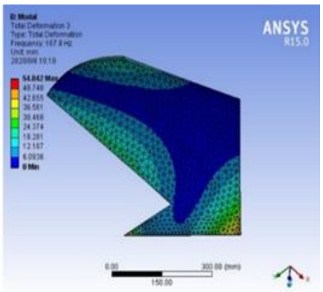
The plow modal shape nephogram of the first six orders is shown in Fig. 5.



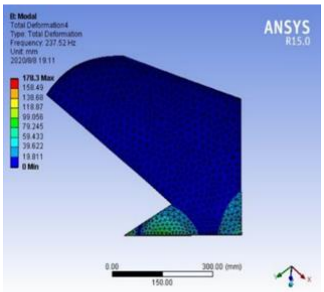
(a) First order modal shape nephogram



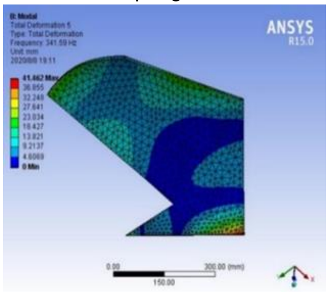
(b) Second order modal shape nephogram



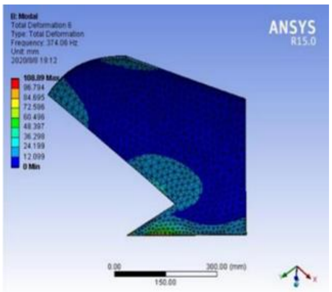
(c) Third order modal shape nephogram



(d) Fourth order modal shape nephogram



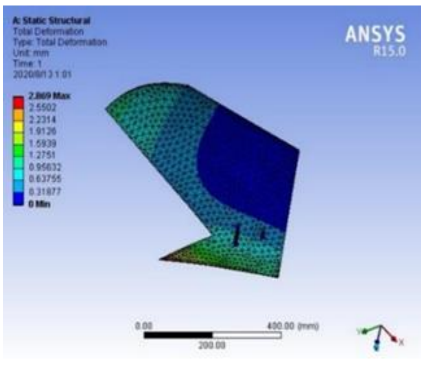
(e) Fifth order modal shape nephogram



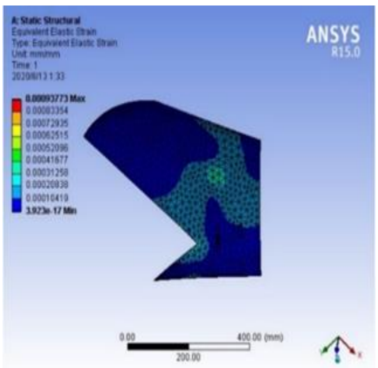
(f) Sixth order modal shape nephogram

Fig. 5 - Plow shape nephogram of the first six orders of modals

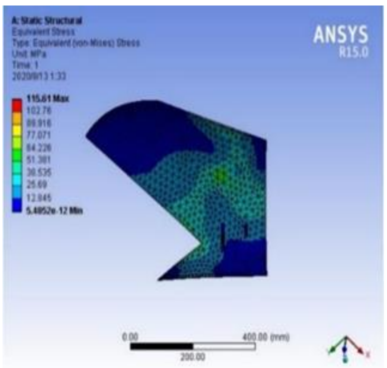
The stress and strain analysis of the plow body was carried out by the ANSYS software. When the tillage speed was 12 km/h, the limit depth was 300 mm, the soil moisture content was 17%, and the soil compactness was 220 KPa, stress distribution of the plow body surface is shown in Fig. 6.



(a) Total deformation nephogram of the plow body



(b) Equivalent strain nephogram of the plow body



(c) Equivalent stress nephogram of the plow body

Fig. 6 - Stress distribution of the plow surface

According to Fig. 6a, the nephogram for the first order modal shape, the total deformation of the plow body was 2.869 mm, and according to the analysis of the equivalent strain nephogram of the plow body in Fig. 6b, the maximum elastic strain was 9.38×10^{-4}; according to the equivalent stress nephogram of the plow body in Fig. 6c, the maximum equivalent stress of the plow body was 115.61 MPa.

RESULTS AND DISCUSSIONS

SOIL BIN TEST

In order to verify the results of the ANSYS static simulation test and the working performance of the optimized high-speed reversible plow, the soil bin test was carried out in the soil bin laboratory of Tarim University, Alar, Xinjiang, China. As shown in Fig. 7, the test sample machine was the optimized high-speed reversible plow. As shown in Fig. 8, the power of the test was driven by the soil bin vehicle (*Zhao et al., 2020*), and the soil bin size was 120m×8m×1m (length×width×height), the test soil was the sandy loam, which is common in south Xinjiang. The average surface flatness was 23.9 mm, the average plant density was 305 g/m^2, and average soil compactness was 225 KPa, and average absolute moisture content of soil was 14.6%.

Test instruments include a straightedge (1 m), a tape measure (5 m), RL-AL type electronic level (Qingdao Rulan Electronics Co., Ltd., with accuracy of 0.002°), portable intelligent tension meter, balance, soil compactness meter (Zhejiang TOP Instrument Co., Ltd., TJSD-750Ⅱ type, ±0.5%FS), soil moisture content meter (Zhejiang TOP Instrument Co., Ltd., TZS-2X type, ±0.01%), fuel consumption meter (Hai-land Intelligent Technology Co., Ltd., with comprehensive accuracy ±0.05%), and electronic second chronograph.

At the beginning of the test, the tillage depth was controlled to be 300 mm by adjusting the depth wheel, the test was carried out based on National standard Moldboard Plough-Test Method (GB/14225.3-93) and Moldboard Plough-Technical Requirements (GB/T14225.2-93) and related reference (*Wei et al., 2020*).

Fig. 7 - Ground surface condition before the test

Fig. 8 - Optimized high-speed reversible plow

The test results obtained in the soil bin laboratory showed that, the traction on the optimized high-speed reversible plow and common high-speed reversible plow made in China was 2227 N and 2572 N, respectively; and the tillage resistances were 34.2 KPa and 40.3 KPa respectively; the tillage resistance on the optimized high-speed reversible plow was 17.9% lower than that on the common high-speed reversible plow made in China. The tillage quality indexes such as coverage rate, soil crushing rate, oil consumption of the optimized high-speed reversible plow was better than that of the common high-speed reversible plow made in China, thus the optimized plow could meet the national standard in terms of working performance.

Table 5

Soil bin test of the optimized high-speed reversible plow

No.	Tillage resistance (kPa)	Traction force (N)	Tilling width (mm)	Tilling depth (mm)	Soil crushing rate (%)	Tillage speed (km/h)
1	33.5	2254	314	297	79.1	10.25
2	348.	2184	315	298	80.1	10.25
3	33.6	2279	320	295	79.6	10.26

Table 5
(continuation)

Soil bin test of the optimized high-speed reversible plow

4	35.1	2365	315	294	79.4	10.25
5	34.3	2279	310	296	79.3	10.24
6	33.9	1985	315	290	79.4	10.25
7	34.5	2019	316	285	78.5	10.25
8	35.2	2308	318	301	78.9	10.24
9	33.1	2281	315	300	79.2	10.24
Mean value	34.2	2227	315	295	79.2	10.25
Extreme value	2.1	380	10	11	0.16	0.02

Table 6

Soil bin test results of the common high-speed reversible plow made in China

No.	Tillage resistance (KPa)	Traction force (N)	Tilling width (mm)	Tilling depth (mm)	Soil crushing rate (%)	Tillage speed (Km/h)
1	40.1	2497	311	284	75.8	10.25
2	40.5	2563	305	298	73.4	10.25
3	39.6	2580	308	286	74.8	10.26
4	39.8	2631	301	294	74.2	10.25
5	42.2	2587	302	296	75.4	10.24
6	40.7	2491	311	292	75.1	10.25
7	40.5	2581	304	297	74.4	10.25
8	38.9	2687	304	298	76.3	10.24
9	40.3	2534	297	292	75.1	10.24
Mean value	40.3	2572	304	293	74.9	10.25
Extreme value	3.3	196	14	14	0.29	0.02

CONCLUSIONS

(1) In this paper, a kind of high-speed reversible plow suitable for tillage in farmlands in South Xinjiang in China was designed. The plow can reduce tillage resistivity through changing the structure of the plow. When the limit depth was 300 mm, tillage speed was 12 km/h, the influence of different factors of the plow body on tillage resistivity was analyzed, and plow height had very significant influence on tillage resistivity. Both dozer angle and cutting angle had significant influence on tillage resistivity.

(2) The established quadratic response surface regression equation for the resistivity showed that, in tillage, when depth limit was 300 mm, tillage speed was 12 km/h, cutting angle was 37°, dozer angle was 84°, plow height was 250 mm, then the plow had the optimal tillage resistivity, which was 2.85 $N{\cdot}cm^{-2}$. Compared with the results of numerical analysis, the tillage resistivity could reduce resistance by 8.96%~22.7%, showing that the structural parameters could meet the processing requirements.

(3) The finite element static simulation test showed that, when tillage speed was 12 km/h, depth limit was 300 mm, soil moisture content was 17% and soil compactness was 220 KPa, the total deformation of the plow surface was 2.869 mm, and the maximum elastic strain on the plow surface was 9.38×10^{-4}, the maximum stress on the plow surface was 115.61 MPa.

(4) Soil bin test showed that, the actual depth of the plow was basically consistent with the depth limit, also, the stability of the tilling depth was kept above 95%, so the working performance could meet the agronomic requirements.

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