STUDY ON THE SCOOP ANGLE CHARCTERISTICS OF A HANDHELD TILLER'S ROTARY BLADE
/
微耕机用旋耕弯刀正切刃背角特性研究

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Keywords: *handheld tiller, rotary blade, scoop angle, plane conversion*

ABSTRACT
A mathematical model of scoop angle of the sidelong edge of a handheld tiller's rotary blade was established by plane conversion and angle change. The effects of cornerite of the sidelong edge and bending angle of the blade on scoop angle were studied as well. The results showed that: with increase of the cornerite, scoop angle linearly increases at large; for sidelong edge of cornerite from 30.5 to 45.4°, the corresponding scoop angle increases from 66.6 to 76.6°; for a position, of same cornerite (other parameters remain constant), on the sidelong edge, scoop angle increases with increase of bending angle.

摘要
通过平面转换和角度改变，建立微耕机用刀盘式湿地弯刀正切刃背角的数学模型，研究了正切刃包角和弯折角对正切刃背角的影响。结果表明：随着正切刃包角的增大，正切刃背角逐渐增大，呈近似线性关系；当正切刃包角取值范围为 30.5-45.4°时，对应的正切刃背角为 66.6-76.6°；在其他参数不变的情况下，对于正切刃同一包角位置，正切刃背角随着弯折角的增大而增大。

INTRODUCTION

Handheld tillers are mainly used for such cultivating works as paddy field tillage, upland field tillage, pastoral management and protected agriculture tillage, etc. The rotating tilling parts, namely the rotavators, are directly driven by the drive shaft of a tiller *(Peng, et al, 2014)*. The interaction of rotavator and soil while soil-tilling functions as both "hands" and "feet": the "hands" function includes soil cutting, pulverization, soil turning, soil throwing and soil levelling, etc., and the "feet" function pushes the tiller forward by the soil reacting force from the soil-tilling. The rotavator consists of some rotary blades and a shaft, with rotary blades mounted on the shaft according to a certain arrangement. The sidelong section and lengthwise section of the rotary blade undertake the soil-tilling task, and the geometric parameters of the blade directly affect the performance of a rotavator and the corresponding handheld tiller *(Niu, et al, 2015; Yang, et al, 2015)*. The sidelong section of the blade takes the main responsibility for the soil-tilling and has an important influence on the spraying performance, soil turning and soil throwing. The scoop angle and clearance angle of the sidelong section of a blade are complementary. The scoop angle is one of the main parameters of the sidelong section and has an important influence on the soil-cutting resistance and soil throwing *(Peng, 2014)*. At the present, many scholars made some extensive investigations on scoop angle or clearance angle of the rotary blade. Sakai et al experimentally studied the effects of scoop angle on soil cutting process, and obtained the reasonable range of scoop angle of the rotary blade under different soil conditions *(Sakai, et al, 1984; Sakurai, et al, 1989)*. Ding et al studied the effects of blade edge sharpening way and soil cutting mode on the clearance angle of the rotary blade, and obtained the minimum value of clearance angle of wide-type rotary blade with inside-edged and double-edged curves *(Ding, et al, 1997)*. Matin et al studied the variation of blade clearance angle for a conventional blade with the rotary speed of rotavator from 125 rpm to 500 rpm, analysed the furrowing performance of a straight blade with clearance angle 15° at the position of edge curve tip, and pointed out that the inside-edged blade could enhance furrow backfill to improve seed bed, thereby to improve the germination percentage and seeding vigour after sowing *(Matin, et al, 2015; Matin et al, 2016)*.

In this study, taking the handheld tiller's rotary blade as a case study, the mathematical model of the scoop angle of the sidelong edge of the rotary blade was established by means of plane conversion and angle change. The changing rule of scoop angle with changing of positions of the sidelong edge and the effects of bending angle on the scoop angle characteristics were studied as well. As a result, the study can provide references to the design calculation, force and vibration reduction, and performance optimization for a handheld tiller's rotary blade.

MATERIAL AND METHOD

The rotary blade, adaptable for wetland sticky paddy field tillage, consists of holding section, neck, sidelong section and lengthwise section. It was designed according to Chinese National Standard GB/T 5669-2008 "Rotary tiller-rotary blades and blade holders", Chongqing Standard DB50/T 277-2008 "Blades of micro-cultivator", and Japanese National Standard JIS B 9210-1988 (2008 confirmed) "Blades for tillers". The main design contents of a rotary blade include edge curve, back edge curve, rotation radius *R*, maximum cornerite of the lengthwise edge curve θ_{max}, cutting angle α, bending angle β, bending radius *r* and tilling width *B*, etc., as shown in fig. 1.

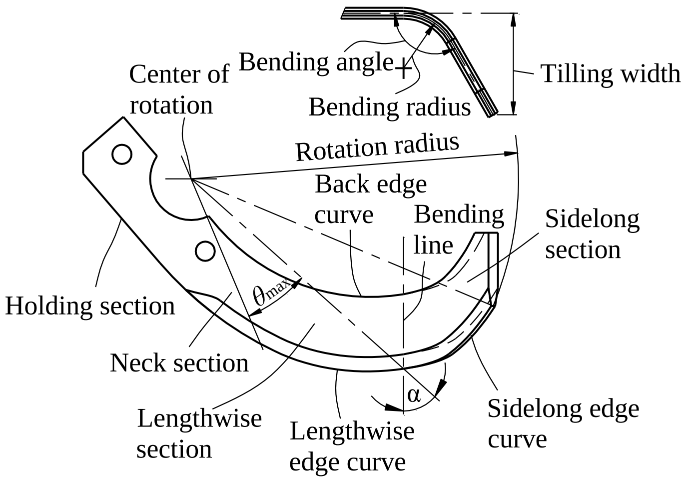

Fig.1 - The structure of a rotary blade

Considering that the rotation radius of the handheld tiller's rotary blade is small, a circular shape back edge curve was adopted. A spiral of Archimedes was adopted for the edge curve, and its equation is as follows:

$$R_n = a_1 R + a_0 R\theta \text{, [mm]} \tag{1}$$

where: R_n is rotation radius at a selected point on the edge curve, [mm];
R – rotation radius of a rotary blade, [mm];
θ – cornerite of the edge curve, [degree];
a_0 and a_1 – constants.

The sidelong section takes the main responsibility for the soil-cutting, and geometric parameters directly affect the performance of a rotavator and the corresponding handheld tiller. While rotary tilling, the trajectory of any point on the sidelong edge is a trochoid. The cross section at any selected point on the sidelong edge was obtained through a section plane, at the selected point, that is perpendicular to the rotation axis of the rotary blade, as shown in fig. 2. β_1 is scoop angle, γ_0 is rake angle, *i* is sharpening angle, δ is clearance angle or relief angle.

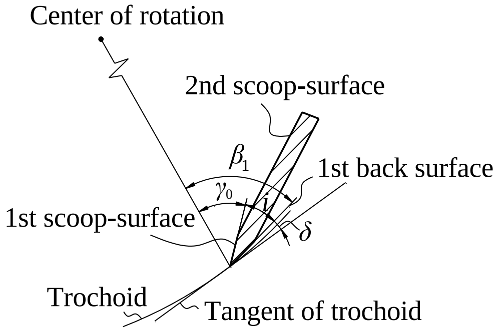

Fig.2 - The cross-section of sidelong section

Numerical method was adopted to analyze the characteristics of the sidelong edge scoop angle of a handheld tiller's rotary blade. A mathematical model of the scoop angle was established by means of plane conversion and angle change.

In order to provide convenience for the build-up of mathematical model of the scoop angle, three planes were defined as follows: plane P_0 is the plane that contains a selected point on the sidelong edge and is perpendicular to the sidelong edge or its tangent, plane P_1 is the plane that contains the selected point and is perpendicular to the plane of sidelong section and parallels to the bending line of the rotary blade, and plane P_2 is the plane that contains the selected point and is perpendicular to the rotation axis of the rotary blade, as shown in fig. 3 and fig. 4. Scoop angle β_1, sharpening angle *i* and clearance angle *δ* are measured in plane P_2.

By plane conversion, dimensions of blade thickness in these three planes are e_0, e_1 and e_2, respectively, and the dimensions of edge width, blade edge surface width, and blade edge surface height in these three planes are as follows correspondingly: c_0, c_1 and c_2; l_0, l_1 and l_2; and h_0, h_1 and h_2. And there are relations of $e_0=e_1$, $c_0=c_1$ and $h_1=h_2$.

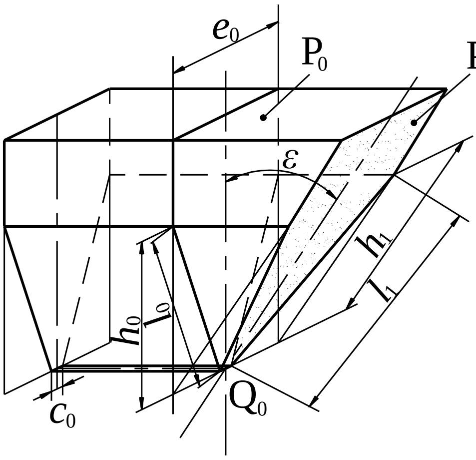

Fig.3 - Apparent section P_0 and actual section P_1 of lengthwise section

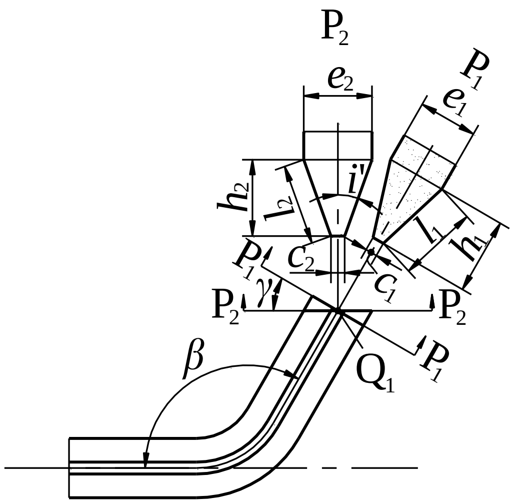

Fig.4 - Sections P_1 and P_2

The scoop angle in plane P_2 can be expressed as follows (see fig. 5):

$$\beta_1 = i' + \varphi \text{ , [degree]} \tag{2}$$

where:

β_1 is scoop angle, [degree];

i' – half-sharpening angle, and $i' = i/2$, [degree];

φ – the angle between rotation radius and bending line on the sidelong edge, [degree].

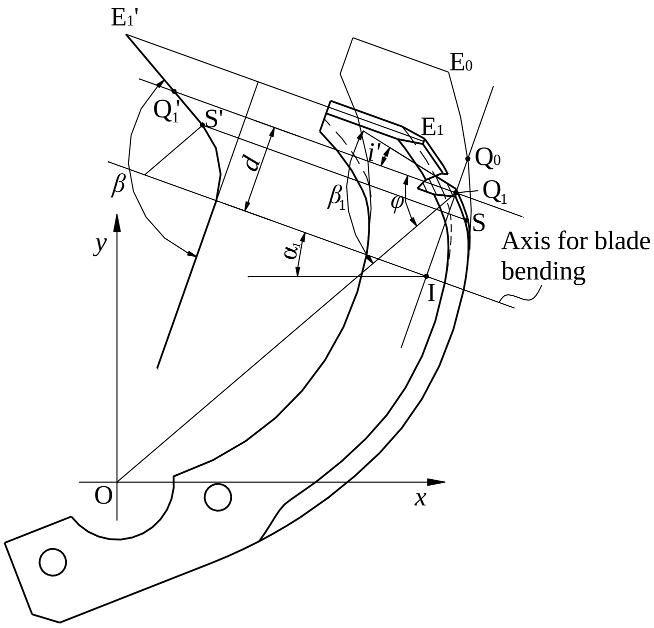

Fig.5 - Schematic paragraph of scoop angle

Half-sharpening angle could be calculated in the cross-section of the cutting edge in P_2, with expression as follows:

$$i' = \arctan\left(\frac{e_2 - c_2}{2h_2}\right), \text{ [degree]} \tag{3}$$

Because e_0=e_1, the thickness of blade e_2 can be expressed as (see Figure 4):

$$e_2 = \frac{e_0}{\cos\gamma}, \text{ [mm]} \tag{4}$$

where:

γ – the angle between plane P_1 and P_2, and $\gamma = \beta - \pi/2$, [degree]. β is bending angle, and it is generally set as 120°.

Similarly, edge width c_2 can be expressed as:

$$c_2 = \frac{c_0}{\cos\gamma}, \text{ [mm]} \tag{5}$$

Since h_1=h_2, the height of the blade edge surface h_2 can be expressed as (see fig. 3):

$$h_2 = \frac{h_0}{\cos\varepsilon}, \text{ [mm]} \tag{6}$$

where:

ε – the angle between the plane P_0 and P_1, [degree];

h_0 – width of the blade edge surface, mm, and $h_0 = \sqrt{l_0^2 - \left(e_0 - c_0\right)^2/4}$, [mm].

By substituting equations (4), (5) and (6) into equation (3), the following expression is established:

$$i' = \arctan\left(\frac{(e_0 - c_0)\cos\varepsilon}{2\cos(\beta - \frac{\pi}{2})\sqrt{l_0^2 - \frac{(e_0 - c_0)^2}{4}}}\right), \text{ [degree]} \tag{7}$$

For calculating the angle between rotation radius and bending line at the selected point on sidelong edge, a Cartesian coordinate system of the edge curve was established, as shown in fig. 5. The selected point Q_0 on the sidelong edge becomes Q_1 by the bending deformation, and their coordinates are (x_0, y_0)

and (*x*, *y*), respectively, and (*x*, *y*) can be calculated according to the fact: the length of the edge curve keeps constant before and after the bending deformation. Then, the angle between rotation radius and bending line at any selected point on the sidelong section can be expressed as:

$$\varphi = \arctan(\frac{y}{x}) + \alpha_1, \text{ [degree]} \tag{8}$$

where:
α_1 – the angle between bending line and x-axis, [degree].

By substituting equations (7) and (8) into equation (2), the mathematical model of scoop angle of the sidelong edge can be obtained as:

$$\beta_1 = \arctan\left(\frac{(e_0 - c_0)\cos\varepsilon}{2\cos(\beta - \frac{\pi}{2})\sqrt{l_0^2 - \frac{(e_0 - c_0)^2}{4}}}\right) + \arctan(\frac{y}{x}) + \alpha_1, \text{ [degree]} \tag{9}$$

RESULTS

Taking the handheld tiller's rotary blade as a case study, the characteristics of the scoop angle of the rotary blade's sidelong edge was studied in this work. The parameters of the rotary blade are defined as shown in table 1, and the edge curve equation of the sidelong section is $R_n = 0.58R + 0.128R\theta$.

Table 1

Parameters of the rotary blade

Parameter	Value	Parameter	Value
Rotation radius of the blade, R [mm]	180	**Blade thickness in plane P_0, e_0 [mm]**	6
Maximum cornerite of lengthwise edge curve, θ_{max} [degree]	22.2	**Edge width in plane P_0, c_0 [mm]**	2.5
Cutting angle at θ_{max}, α [degree]	45.2	**Edge surface width in plane P_0, l_0 [mm]**	8
Bending radius, *r* [mm]	30	**Cornerite at point S, θ_S [degree]**	30.5
Bending angle, β [degree]	120	**Cornerite at point E_1, θ_{E1} [degree]**	45.4
Start Radius of spiral of Archimedes, R_0 [mm]	104.4	**Angle between bending line and x-axis, α_1 [degree]**	23

According to the mathematical model of the scoop angle, scoop angle at positions, with different cornerites, on the sidelong edge of the defined rotary blade could be calculated. Curves of scoop angle, rake angle and sharpening angle of the sidelong edge with cornerite were shown in fig. 6. The sharpening angle is calculated by equation (7), and the rake angle γ_0 is the difference between scoop angle and sharpening angle.

Similarly, scoop angle at positions, with different cornerites, on the sidelong edge of the rotary blade with different bending angles can be obtained by changing bending angle from 115 to 125° and keeping other parameters unchanged as shown in table 1. The curves of scoop angle with bending angle were shown in fig. 7.

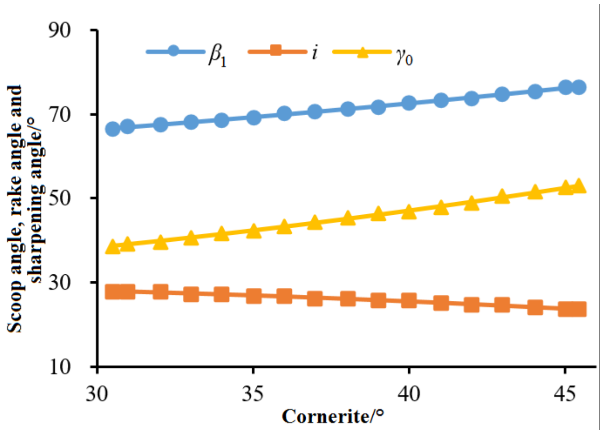

Fig.6 - Curves of scoop angle, rake angle and sharpening angle with cornerite

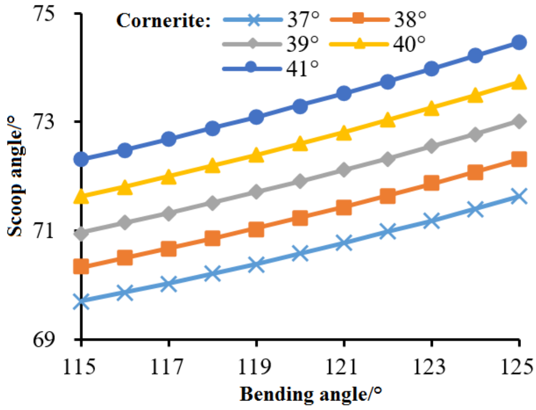

Fig.7 - Curves of scoop angle with bending angle

As can be seen from fig. 6, with the increase of cornerite of the sidelong edge, the scoop angle increases. For the rotary blade with parameters listed in Table 1, the cornerite of the sidelong edge of the linear section ranges from 30.5 to 45.4°, and the corresponding scoop angles linearly increase from 66.6 to 76.6° at large. Note: this linear section refers to section of sidelong edge starting from point S to E_1, namely, not including the bending part of the sidelong section.

According to literature *(Sakai, et al, 1984)*, with the increase of scoop angle, soil-cutting resistance decreases and the soil-throwing performance degrades, and it is recommended that the general scoop angle ranges as follows: 40-55° for soft soil such as sandy or muddy soil, 55-75° for normal soil such as sandy loam, loam or clay loam, 75-85° for hard soil such as heavy clay or dry soil. The scoop angle of the rotary blade with parameters listed in table 1 ranges within 66.6-76.6°, which indicates that the rotary blade is suitable for tilling in loam and clay loam, and is consistent with the application situation of such soil type as wet and sticky soil of the rotary blade studied.

In fact, the main reason for soil-cutting resistance decrease with the increase of scoop angle is as follows: the rake angle increases with the increase of sidelong edge's cornerite, and the larger rake angle, the shaper the edge, and as a result, the smaller the soil-cutting resistance. At the same time, the increase of rake angle leads to the decrease of deformation level of the soil out-flowing from the scoop surface, which results in the decrease of soil-cutting energy consumption. The deformation decrease leads to the degrading of performance of soil-throwing. However, the clearance angle decreases with the increase of scoop angle on the sidelong edge, which results in the increase of friction between back surface of the sidelong section and soil.

In addition, with the increase of cornerite of sidelong edge, the actual sharpening angle decreases, which makes the blade edge sharper and benefits the blade on the soil-cutting resistance reduction. However, the decrease of actual sharpening angle results in the easy worn-out of the sidelong edge, and the worn-out of edge close to the blade tip is more serious.

According to literature *(Ding, et al, 2004)*, 50-80% of energy consumption of tilling is consumed by soil-cutting of sidelong section of a rotary blade. As the main angle parameter of sidelong section, the scoop angle has crucial relations with rake angle and clearance angle of the sidelong edge while sharpening angle keeps constant. As a result, the scoop angle is an angle parameter that reflects the comprehensive effect of rake angle and clearance angle of the sidelong edge, and it has an important influence on the soil-cutting resistance and soil-throwing performance of the rotary blade.

As shown in fig. 7, for a position, with the same cornerite (while other parameters remains constant), on the sidelong edge, the scoop angle increases with the increase of the bending angle of the rotary blade. This is beneficial to the soil-cutting resistance reduction but it results in the soil-throwing performance degrading. The bending angle falls into range of 115-125º in this study.

At the same time, for rotary blades of different bending angle, the scoop angle increases with the increase of cornerite of the sidelong edge, which is consistent with the aforementioned effect of cornerite on characteristics of scoop angle.

In practical selection, the bending angle should be determined under comprehensive consideration, and the recommended value for the bending angle of a rotary blade is 120º by Chinese standard GB/T 5669-2008.

CONCLUSIONS

The sidelong section of a rotary blade takes the main responsibility for soil-cutting. The scoop angle is one of the main parameters of the sidelong section and has an important influence on the soil-cutting resistance and soil throwing. Taking the handheld tiller's rotary blade as a case study, the mathematical model of the scoop angle of the sidelong edge of the blade was established by means of plane conversion and angle change. The main conclusions are as follows:

(1) With increase of cornerite of the sidelong edge, scoop angle linearly increases at large. For sidelong edge of cornerite ranging from 30.5 to 45.4°, the corresponding scoop angle increases from 66.6 to 76.6°, which indicates that the rotary blade is suitable for tilling in loam and clay loam, and it is consistent with the application situation of the soil type of the rotary blade studied.

(2) For a position, with the same cornerite (other parameters remains constant), on the sidelong edge, scoop angle increases with increase of bending angle of the rotary blade. This is beneficial to the soil-cutting resistance reduction.

(3) The scoop angle is an angle parameter that reflects the comprehensive effect of rake angle and clearance angle of the sidelong edge. The scoop angle has crucial relations with rake angle and clearance angle of the sidelong edge while sharpening angle keeps constant, and it has an important influence on the soil-cutting resistance and soil-throwing performance of the rotary blade.

ACKNOWLEDGEMENT

The work has been funded by Fundamental Research Funds for the Central Universities of China (XDJK2014C033), Ph.D. Research Project of Southwest University (SWU115011), and Fund from Key Laboratory of Modern Agricultural Equipment, Ministry of Agriculture, P. R. China (2016-001).

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