Journal of Applied Mechanical Engineering

Mandal et al., J Appl Mech Eng 2015, 4:3
DOI: 10.4172/2168-9873.1000164

Research Article Open Access

Design of Rotary Tiller's Blade Using Specific Work Method (SWM)

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Abstract

Tillage is an operation performed to obtain a desirable soil structure for a seedbed. A granular structure is desirable to allow rapid infiltration and good retention of rainfall, to provide adequate air capacity and exchange within the soil and to minimize resistance to root penetration. Rotary tiller or rotavator (derived from rotary cultivator) is a tillage machine designed for preparing land by breaking the soil with the help of rotating blades suitable for sowing seeds (without overturning of the soil). Nowadays, utilization of rotary tillers has been increased in agricultural applications because of simple structure and high efficiency. However in a rotary tiller, blades are the main critical parts which engaged with soil to prepare the land. These blades interact with soil in a different way than normal plows that are subjected to impact load and high friction which ultimately creates unbalancing and non-uniform forces on the rotary tiller. This result wears in the blades. Therefore, it is necessary to optimize the design of blade so that wear will minimum and thereby enhanced the service life. The present research has dealt with design of "L" type blade for tractor drawn Rotary tiller or Rotavator using Specific Work Method (SWM).

Keywords: Rotary tiller; Blade; Wear; SWM; Tillage

Introduction

A rotary tiller is a specialized mechanical tool used to plough the land by a series of blades which are used to swirl up the earth. Rotary tillers have become world famous for preparation of seedbed Rotary tillers have become world famous for preparation of seedbed in fields. This equipment's are often used for breaking or working the soil in lawns, gardens, etc., [1]. Nowadays, utilization of rotary tillers has been increased in agricultural applications because of simple structure and high efficiency for this type of tillage implements. By taking advantage of rotary tillers, the primary and secondary tillage applications could be conjugated in one stage [2]. Despite of their high energy consumption, since rotary tillers have the ability of making several types of tillage applications in one stage, the total power needed for these equipment's is low [3]. Because rotary tillers power is directly transmitted to the tillage blades, the power transmission efficiency in rotary tillers is high. Power to operate the rotary tiller is restricted by available tractor power [4,5].

Rotavators are mostly available in the size of 1.20–1.80 m working width and which is suitable for tractors having 45 hp and above. Further, rotavator may have 'L' shape, 'C' shape, 'J' shape, hook tines and straight knife blades to suit various operating conditions (Figure 1). Generally, L-shaped blades are used in Indian rotavator. The work quality by using a rotavator not only depends on design parameters but rotor blade layout, speed of rotors, forward speed significantly affects the machine performance. When a tillage operation is performed in the field, the soil texture will be a function of soil conditions, blade geometry and soil flow dynamics. Depending on the soil conditions, blade geometry and velocity ratio, the interference of the backside of the blade and the uncut soil may result in severe soil compaction and high power consumption. This is the main reason to cause vibrations, which are a result of the reaction of soil upon the tiller blades. The proper design of the rotary tiller blades is essential to efficient operation [6]. The matrix equations for describing the motion of the blade of rotary tiller were described by [7]. Chen et al. [8] demonstrated that energy consumption in rotary tillage can be decreased through improved blade design. In maize and spring barley production systems in combination with a chisel plow, rotary tillers have been found to have high energy requirements, but rotary tilling is more effective in saving labor compared to conventional tillage systems [9]. The continuous fluctuating impact of soil crust/clods/stone develops high stress areas on blade tip or blade critical edges. A rotavator has a useful life of 2400 h (8 year) with annual use hour as 300.The local blades need replacement after 80-200 h of their use; however, imported blades need replacement after 300-350 h in normal soil. The local and imported blade sets are changed 23 times and 7 time respectively during their entire service life. It is estimated that around 5 lakhs blades are required annually towards replacement and for new machines [10]. Therefore, proper design of these blades is necessary in order to increase their working life time and reduce the farming costs [11]. In India, because of variety of soil conditions in different regions, different blades are used, but most of the blades faces similar problem like high rate of wear which ultimately reducing the service life/working life. Working life time of the blades can be increased by a suitable design according to the soil type and soil condition. In India, because of variety of soil conditions in different regions, different blades are used, but most of the blades faces similar problem like high rate of wear which ultimately reducing the service life/working life. Working life time of the blades can be increased by a suitable design according to the soil type and soil condition. Hence, the object of this study was to design suitable rotary tiller blade design optimization using finite element analysis method to increase the useful life of the tiller blade in order to reduce the idle time required to replace the blade periodically during soil preparation shown in Figures 1 and 2.

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Received February 12, 2014; **Accepted** March 26, 2015; **Published** March 31, 2015

Citation: Mandal S, Bhattacharyya B, Mukherjee S (2015) Design of Rotary Tiller's Blade Using Specific Work Method (SWM). J Appl Mech Eng 4: 164. doi:10.4172/2168-9873.1000164

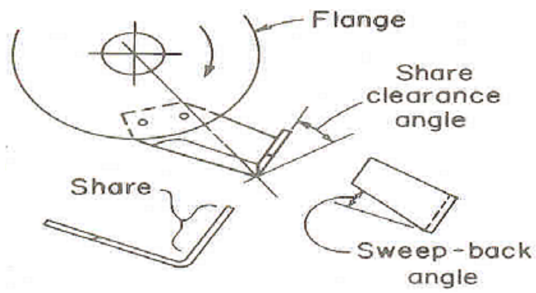

Figure 1: Three views of an L-shaped blade for rotary tiller [16].

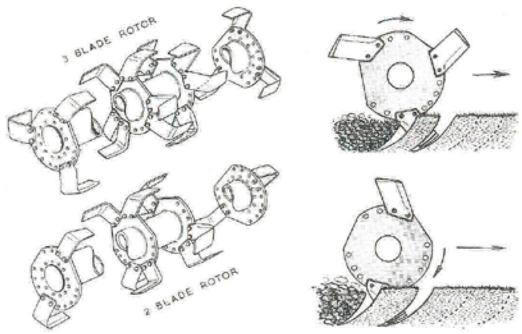

Figure 2: Rotary tiller rotors with L-type blades showing methods of mounting and cutting action [3].

Tillage

Tillage may be defined as the mathematical manipulation of soil to develop a desirable soil structure for seedbed or root-bed, to control weeds, to manage plant residues, to minimize soil erosion and to establish specific surface configurations for planting, irrigation etc. Tillage operations for seedbed preparations are often classified as primary or secondary. A primary tillage operation constitutes the initial, major soil-working operations; it is normally designed to reduce the soil strength. Secondary tillage operations are intended to create refined soil conditions. The moldboard plow is most commonly used for primary tillage. Rotary tiller's or rotavators are being used now days as a secondary tillage implements as these tool obtain their energy in more than one manner, energy from a rotary source usually the tractor PTO. Reduced draft requirements and greater versatility in manipulating the soil to obtain a desired result are the two reasons for considering these more complex types of equipment's. If draft requirements can be reduced by utilizing at least part of tractor's output through PTO, the tractor can be made lighter which will reduce its cost and reduce soil compaction. Therefore it becomes necessary to use minimum tillage systems for the purpose of to reduce the mechanical energy and labor requirements, to conserve moisture and to minimize the number of trips over the field. Rotary tiller is the perfect machine suitable for the minimum tillage system. The high degree of pulverization does make rotary tillers good seedbed preparation. Rotary tillers are also good for cutting up vegetable matter and mixing it throughout the tilled layer. Rotary tillers are widely used for rice in Japan Kawamura [12] and other Asiatic countries. Rice paddies in these countries are often "puddled" by means of underwater rotary tillage. The rotor usually rotates in the same direction as the tractor wheels. Each blade cuts a segment of soil as it moves downward and toward the rear as shown in Figure 3. Most rotary tillers make either 2 or 3 cuts per revolution. Because of the high peak torques developed during each cut, it is important to stagger the blades in the different courses, with equal angular displacement between them, so no two blades strike the soil at the same time.

Materials and Methods

Technical characteristics of the rotary tiller

For designing the rotary tiller blade, a tractor of 12 hp was considered as the rotary tiller power supply.

The technical characteristics of the tractor are presented in Table 1.

Specific work method (SWM)

In order to design a rotary tiller, the special work of the tiller and also the performable work of the tractor should be determined. The specific work of rotary tiller is defined as the work carried on by rotary tiller at each rotation of tillage blades per the volume of broken soil, which could be calculated by the following equation [13]:

$$A = A_0 + A_B \quad \frac{kg-m}{dm^3} \tag{1}$$

Where A0 and AB are the static specific work and dynamic specific work of rotary tiller (kg-m/dm3) respectively, which can be calculated from the following equations:

$$A_0 = 0.1C_0K_0 \quad \frac{kg-m}{dm^3} \tag{2}$$

$$A_B = 0.001a_u u^2 \quad \frac{kg-m}{dm^3} \tag{3}$$

$$A_B = 0.001a_v v^2 \quad \frac{kg-m}{dm^3} \tag{4}$$

Where: C_o is the coefficient relative to the soil type, K_o is the specific strength of soil (kg/dm^3), u is the tangential speed of the blades (m/s), v is the forward speed (m/s), a_u and a_v are dynamical coefficients that are

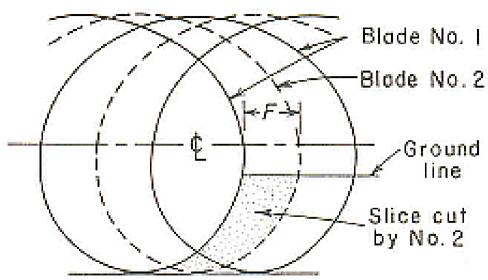

Figure 3: Paths of cutting edges or tips for 2 blades 1800 apart, in relation to forward travel (Kepner et al., 1977).

Sl. No.	Specification	Value
01	No. of cylinder	1
02	Maximum Engine power at 3000 rpm	12 hp
03	Maximum Torque at 2400 rpm	3.2 kg-m
04	PTO speed	1000 rpm
05	Total weight	830 kg

Table 1: Technical characteristics of the tractor.

relative together throw the following equation:

$$a_v = a_u \lambda^2 \quad \frac{kg - s^2}{m^4} \tag{5}$$

Where

$$\lambda = \frac{u}{v} \tag{6}$$

The performable work of the tractor (Ac) could be calculated by the following equation Bernacki [13]:

$$\frac{7.5 \quad {}_c\eta_c \eta_z}{vab} \quad \frac{kg \quad m}{dm} \tag{7}$$

Where: N_c is the power of tractor (hp), v is the forward speed (m/s), is the traction efficiency that its value for the forward rotation of the rotary tiller shaft is 0.9; Whilst the value for the reverse rotation of the rotary tiller is considered between 0.8-0.9, is the coefficient of reservation of tractor power which is between 0.7-0.8, a is the rotary tiller work depth (dm) and b is the tiller work width (dm) [14].

Matyashin [15] reported that at the forward rotation of the rotary tiller shaft, the tillage power consumption is decreased 10-15 %, in comparison with the shaft reverse rotation. Hence, in this design the forward rotation was considered for the rotary tiller shaft to reduce the tractor power consumption and also utilization of the rotary tiller thrust force at the forward rotation. In designing the rotary tiller, the hard condition of the soil was considered. The values of C_o, K_o and a_u in very heavy soils are 2.5, 50 (kg/dm^3) and 400 kg.s^2/m^4, respectively [13]. Therefore, the static special work of the rotary tiller could be calculated by replacing the values in the equation (2):

$$A_0 = 0.1 \times 2.25 \times 50 = 11.25 \quad \frac{kg - m}{dm^4}$$

Since the values of b, v and a_v are not given in the equations (4), (5) and (7); a proper domain should be defined for the values at first, with respect to the technical specifications of the selected tractor for this design. Then, the optimum condition for the rotary tiller design could be selected from the domain. The recommended work width for the tractor is 90 cm. The distance between rotary tiller flanges in this design was considered equal to 20 cm. Therefore, the work width domain of the rotary tiller that is the multiple of the distance between the flanges is in the range of 80, 90,100 and 110. This range was selected with respect to the tractor work width. The forward speed of the tractor at different transmission gears are presented in Table 2.

Because at the high levels of tractor forward speeds, the penetration ability of the rotary tiller blades in the soil reduces, in this design only the heavy transmission gears were considered as the domain of forward speed. Hendrick and Gill [1] suggested the minimum value of 2.5 for λ. Hence, a domain from 2 to 22 and from 0.2 to 2 was considered for

Gear	Forward speed (Kmph)	Forward speed(m/s)
1st	1.6	0.4
2nd	2.6	0.7
3rd	3.9	1.08
4th	6.9	1.91
5th	12	3.33
6th	17	4.72
Rev1	1.6	0.4
Rev2	2.6	0.7
Rev3	3.9	1.08

Table 2: Speeds of the selected tractor.

and forward speed, respectively, to provide a large section range for the rotary tiller design.

According to the explanations offered above and by equations (1), (4) and (7), the values of A and Ac could be calculated:

$$A = A_0 + A_B = 11.25 + 0.001 a_v v^2 \tag{8}$$

$$A_c = \frac{43.87}{vb} \tag{9}$$

Where a=1.5 dm=150 mm

By using equations (8) and (9), the values of A *and* A_c with respect to the defined domain for λ and v are obtained in Table 3 Mohammadi Alasti [15].

The proper selection of the forward speed is dependent to the tangential speed of the blades (that is a function of rotational speed of rotor) and the length of sliced soil. The tangential speed of the blades (u), the rotational speed of the rotor (n), and the length of sliced soil (L) could be obtained by the following equations:

$$u = \frac{2\pi n R}{6000} \tag{10}$$

$$\frac{6000}{\quad} \tag{11}$$

$$L = \frac{2\pi R}{\lambda Z}$$

Where

R=Rotor radius (cm)

v=forward velocity (m/s)

Z=number of blades on each side of the rotor flanges

In this design, three blades were considered on each side of the flanges (Z=3). The working depth selected for the rotary tiller in this design was 15 cm. The conventional diameter for rotary tillers rotor is variable from 30 to 50 cm. Moreover, the radius of rotor for rotary tillers should be selected greater than the working depth [14]. Considering these explanations, a 50 cm diameter was diagnosed to be appropriate for the rotary tiller rotor. By replacing the selected value for the rotor diameter in the equations (11) and (12), we will have:

$$n = \frac{6000\lambda v}{2\pi R} = \frac{6000\lambda v}{2\pi \times 25} = 38.21\lambda v \tag{13}$$

$$L = \frac{2\pi \times 25}{\lambda \times 2} = \frac{25\pi}{\lambda} \tag{14}$$

The total possible selections for the rotary tiller working width (b), forward speed (v) and rotational speed of rotor (n) are presented in Table 4. Table 4 is obtained through equations (13) and (14). Firstly, for each of the selected working widths in Table 3, the closest value of the rotary tiller specific work to the performable work of the tractor was determined at each of the forward speeds. Then, the corresponding values of λ for each forward speed were determined to calculate the rotor speed and the length of sliced soil (Table 3). By selecting the rotary tiller specific work and the performable work of the tractor close together at each of the forward speeds, an appropriate conformity will be continued between the rotary tiller and tractor.

Kepner [16] reported that the power needed of the tractor PTO for

		Gear no.			**1 high**			**2 high**		**3 high**				
λ =u/v	a_v	**v(m/s)**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**1.08**	**1.2**	**1.4**	**1.6**	**2**
2	1600		11.31	11.39	11.50	11.65	11.83	12.0	12.27	13.11	13.55	14.38	15.35	17.65
3	3600		11.39	11.57	11.83	12.15	12.55	13.0	13.55	15.44	16.43	18.31	20.47	25.65
4	6400		11.51	11.83	12.27	12.85	13.55	14.38	15.35	18.71	20.47	23.79	27.63	36.85
6	14400		11.83	12.55	13.55	14.85	16.43	18.30	20.47	28.0	31.98	39.47	48.11	68.85
8	25600		12.27	13.55	15.35	17.65	20.47	23.79	27.63	41.10	48.11	61.43	76.78	113.65
10	40000	A (kg-m/dm³)	12.85	14.85	17.65	21.25	25.65	30.85	36.85	57.90	68.85	89.65	113.65	171.25
12	57600		13.55	16.43	20.47	25.65	31.98	39.47	48.11	78.43	94.19	124.15	158.71	241.65
14	78400		14.38	18.30	23.79	30.85	39.47	49.66	61.43	91.44	124.15	164.91	211.95	324.85
16	102400		15.35	20.46	27.63	36.85	48.11	61.42	76.78	130.6	158.71	211.95	273.39	420.85
18	129600		16.43	22.91	31.98	43.65	57.91	74.75	94.19	162.4	197.87	265.27	343.03	529.65
20	160000		17.65	25.65	36.85	51.25	68.85	89.65	113.65	197.8	241.65	324.85	420.85	651.25
22	193600		18.99	28.67	42.23	59.65	80.95	106.1	135.15	237.0	290.03	390.71	506.87	785.65
b (dm)	9	A_c (kg-m/dm³)	24.37	16.24	12.18	9.74	8.12	6.96	6.09	4.51	4.06	3.48	3.04	2.43
	10		21.93	14.6	10.96	8.77	7.31	6.26	5.48	4.06	3.65	3.13	2.74	2.19
	11		19.94	13.29	9.96	7.97	6.46	5.69	4.98	3.69	3.32	2.84	2.49	1.99
	12		18.27	12.18	9.13	7.31	6.09	5.22	4.56	3.38	3.04	2.61	2.29	1.82

Table 3: The values of specific work of rotary tiller and maximum work of tractor at different values of v and λ.

Selection no.	**Working width, cm**	**Forward speed (m/s)**	λ	**Rotor rpm**	**Bite length**	**Difference between *A* and tractor maximum work (kg-m/dm³)**
1	90	0.2	22	168.12	3.57	5.38
2		0.3	10	114.6	7.85	0.89
3		0.4	3	45.85	26.16	0.35
4		0.5	2	38.21	39.25	1.91
5		0.6	2	45.85	39.25	3.71
6	100	0.2	22	168.12	3.57	2.94
7		0.3	8	91.7	9.81	1.05
8		0.4	2	30.56	39.25	0.54
9		0.5	2	38.21	39.25	2.88
10		0.6	2	45.85	39.25	4.52
11	110	0.2	22	168.12	3.57	0.95
12		0.3	6	68.77	13.08	0.74
13		0.4	2	30.56	39.25	1.54
14		0.5	2	38.21	39.25	3.53
15	120	0.2	6	45.85	13.08	0.62
16		0.3	2	22.92	39.25	0.35
17		0.4	2	30.56	39.25	2.52

Table 4: Difference between the rotary tiller specific work and the performable work of the tractor.

supplying a rotary tiller should be approximately 1 hp for each cm of working width. Considering the suitable domain obtained for the rotor speed, the length of sliced soil and the forward speed, at the working width of 120 cm, this width was selected as a proper working width for the tractor. Moreover, at the selected working width there was a little difference between the rotary tiller specific work and the performable work of the tractor (Table 4).

Considering the results presented in Tables 1 and 2, it becomes evident that the selected tractor for this design only at the gear one can supply a rotary tiller with the working width of 110 cm and working depth of 15 cm. After specifying the appropriate working width for the power tiller, the length of sliced soil, the rotational speed of the rotor and the tangential speed of the blades should be calculated at the selected gear (the forward speed of 0.40 m/s). Before performing the mentioned calculations, the appropriate value of proportional to the selected forward speed for the power tiller should be obtained. For this purpose, the specific work of the rotary tiller and the performable work of the tractor should be equal together. Therefore, we will have:

$$Gear\,No.:1 \rightarrow v = 0.4\,m/s \xrightarrow{A=A_c} \lambda = 2.3$$

By representing the obtained value for λ at the equations (10), (11) and (12) we will have:

$$L = \frac{25\pi}{\lambda} = 34.2 \text{ cm}$$

n= $38.21\lambda v = 35.15$ rpm

u=0.92 m/s

For designing the rotor shaft, the maximum tangential force which can be endured by the rotor should be considered. The maximum tangential force occurs at the minimum of blades tangential speed is calculated by the following (Bernacki et al., [12]:

$$K_s = C_s \frac{75 N_c \eta_c \eta_z}{u_{\min}} \tag{16}$$

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Where C_s is the reliability factor=1.5 for non-rocky soils

=2 rocky soils

From equations (6) and (12) it is evident that is obtained at and is obtained at $\lambda_{\min}$ is obtained at $L_{\max}$. So, we will have:

$$\lambda_{\min} = \frac{2\pi R}{ZL_{\max}} = \frac{2\pi \times 25}{3 \times 34.2} = 1.53$$

$$u_{\min} = v\lambda_{\min} = 0.4\text{x}1.5 = 0.6 \text{ m/s}$$

By representing the values of and in equation (16), the maximum tangential force on the tiller shaft will be obtained:

$$K_s = 1.5 \times \frac{75 \times 12 \times 0.9 \times 0.75}{0.6} = 1518.75 \text{ kg}$$

Rotary tiller blades design

The design of rotary tiller blades depends on the type and number of the blades and also the working condition of rotary tiller. In this design, the L type blades were considered for the rotary tiller according to the working condition presented. In rotary tillers, one fourth of the blades action will be jointly on the soil. The total power of the machine is distributed between the blades. The number of rotary tiller flanges (i) can be calculated by the following equation:

$$i = \frac{b}{b_i} = \frac{120}{20} \approx 6$$

Where b is the working width and bi is the distance between the flanges on the rotor. Six blades are considered on each of the flanges. Therefore the total number of blades is obtained:

$$N = i \times Z_e = 6 \times 6 = 36$$

The soil force acting on each of the blade (K_e) is calculated by the following equations:

$$K_e = \frac{K_s C_p}{i Z_e n_e}$$

Where K_s=maximum tangential force, kg

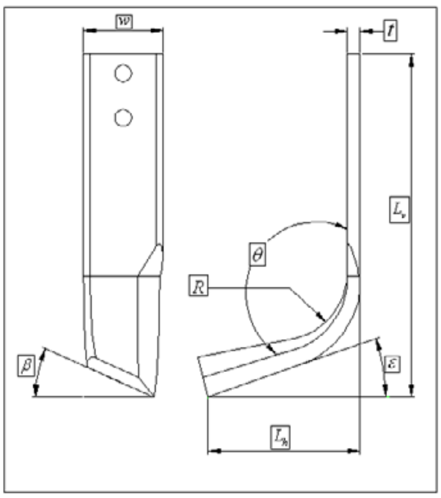

Figure 4: Blade schematic with designed parameters.

Parameters	Notations	Values
w	Blade span, mm	40
L_v	Effective vertical length, mm	212
L_h	Blade cutting width, mm	88.7
R	Curvature between L_v and L_h mm	40
θ	Blade angle, degree	108
β	Clearance angle, degree	20
t	Blade thickness, mm	8.0
ε	Bending angle, degree	22

Table 5: Parameters of different blades designed for the study.

C_p=coefficient of tangential force

i=number of flanges

Z_e=is the number of blades on each side of the flanges

n_e is obtained through division the number of blades which action jointly on the soil into the total number of blades. Considering these definitions, K_e can be calculated:

$$K_e = \frac{K_s C_p}{i Z_e n_e} = \frac{1518.75 \times 2}{6 \times 6 \times \frac{1}{4}} = 337.5 \text{ kg}$$

The dimensions of the blades are defined and presented in Figure 5. Table 5 shows the values of the different parameters defined for the deigned blade in this study.

Conclusion

Optimal working width rotary tiller proportionate to a small tractor with 12 hp capacity were determined in order to achieve to the maximum field efficiency for the rotary tiller and to minimize the consumed materials in the building of this machine. The rotary tiller was designed with the working width of 120 cm having 6 flanges on the rotor shaft and six blades on each flange. It was also concluded that the tractor selected for supporting the rotary tiller, could only pull the rotary tiller efficiently with good penetration at first heavy gear. This paper presents a theoretical method for rotary tillers design. The results of this study should be verified by further tests on rotary tillers according to the results offered in this paper.

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