Optimal design of rotary tiller's rotor and width proportionate to tractor power using energy method

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Abstract: The goal of the modern farming systems is to economize energy consumption and to reduce farming costs. Proper selection and use of agricultural machines are important factors to achieve this end. Rotary tillers are tillage tools that are used for accomplishment of both the primary and secondary tillage practices. Considering the widespread application of rotary tillers and wide use of modern tractors in Iran, optimal design of these machines is mandatory. Therefore in this study, the optimal working width and optimal diameter of the rotary tiller's rotor proportionate with the power of the MF 399 tractor was delineated based on the energy method. This theoretical method is based on the specific works of tractor and rotary tiller. Results showed that the optimal working width and optimal diameter of the rotary tiller's rotor with maximum of forward speed 1 m/s for tractor was 240 cm and 6.27 cm, respectively.

Keywords: Rotary tiller, optimal design, working width, rotor, MF 399

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1 Introduction

Arrival of Engine power on agriculture farms leads to introducing the new machines for farm operations. Employing rotating machines in preparing the soil has increased during recent years[1]. Rotary tillers are the tillage machine used for accomplishment both the primary and secondary tillage operations. Rotary tiller is a tillage machine used in arable field and fruit garden in agriculture. This machine has a huge capacity for cutting, mixing topsoil and preparing the seedbed preparation directly. Additionally, a rotary tiller has a mixing capacity seven times more than a plough. This tool decreases the soil traffic to a great extent by blending the soil. Using rotary tiller is increasing nowadays because of its various benefits[2,3].

Rotary tillers are classified as active implements. In these machines, power is transferred to the tiller from the tractor via the power-take-off drive. A shaft containing blades is located at 90° to the line of travel and rotates in the same direction as the forward travel of the tractor. Since the shaft turns at a rate that is considerably faster than the corresponding tractor speed, soil pulverization is accomplished. Power to operate the rotary tiller is restricted by available tractor power[4,5].

Tillage tools direct energy into the soil to cause some desired effect such as cutting, breaking, inversion, or movement of soil. Soil is transferred from an initial

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condition to a different final condition by this process[6]. Tillage is a major operation for seedbed preparation and is one of the largest material handling operations. It is one of the major items of energy and cost expenditure in crop production. The energy input in soil manipulation is exceeded only by the level of energy input in irrigation[7]. Thus, increasing the effectiveness of tillage tools, even by a small fraction, would amount to a huge saving in energy. It would be rather more economical to increase the productive rate of each machine rather than to increase the number of machines indiscriminately. Most of the tillage and soil engaging tools in use have been developed based on experience and inventiveness. A number of inherent advantages of machines, which transmit power directly to the soil, require that they be considered as alternatives to tools drawn through the soil[2,8].

The improvement of the operational efficiency of tractors has been a subject of considerable research. Operation efficiency can be improved by maximizing the work output or reducing fuel consumption. Potential savings up to 20% could be achieved with the gear-up throttle-down technique[9-12]. The proper matching of an implement to a tractor is another method of increasing operational efficiency. For a specific implement working on a given soil, the magnitude of its draught is a function of travel speed, operating tillage depth and width. The operating cost for any given implement could be minimized either by optimizing the travel speed or the operating width[13].

Kosutic et al [14] found an optimal combination of working factors (working velocity, depth of tillage and peripheral tine velocity) of a rotary cultivator with spike tines with respect to weighted mean diameter of clods, energy requirement and rate of work. It was concluded that increasing the peripheral tine velocity linearly increased the power requirement, but decreased the weighted mean diameter of clods. Nimayapa et al[15] conducted a laboratory investigation of design parameters of a rotary tiller. They reported that the power required increased with an increase of the rotor speed, the forward travel speed and the tilling depth. It was concluded that these parameters also affected soil breakage.

Maximum exploitation from available energy is one of the main goals of modern farming systems. Optimal design of agricultural machines proportionate to the present tractor power must be considered in order to achieve this goal[16]. This leads to an increase in farm effective efficiency, saving time in the farm operation, and maximizing the use of tractor power. Nowadays no efficient method has been developed to determine the optimal characteristics of rotary tiller's tillage components. Hence, the present research was undertaken to determine the optimal working width and diameter of rotary tiller proportionate to the power of Massey Ferguson 399 tractor that is the most newly and commonly used tractor on the farms of Iran. This paper presents a new theoretical approach in order to design main tillage components of rotary tillers.

2 Materials and methods

The design of rotary tiller's rotor was based on the power of the Massey Ferguson 399 (MF 399) tractor. Technical specifications of this tractor are shown in Table 1[17].

Table 1 Technical specifications of the MF 399 tractor

Specification	Value
Engine maximum power at 2000 r/min, kW	80.9
Engine maximum torque at 1200 r/min, N.m	430
Rotational speed of Power Take off Shaft (PTO) at 1842 r/min of engine rotational speed, r/min	540
PTO maximum power, kW	70.4

Design of main parameters of rotor (see Figure 1) was based on the energy method. In this method for determining the power consumption of rotor, two

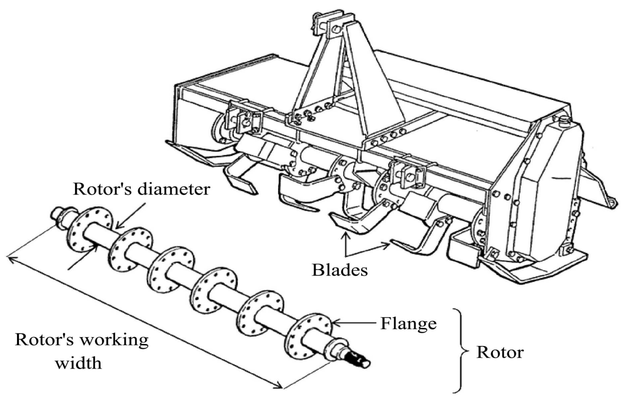

Figure 1 Tillage components of rotary tiller and main parts of rotor

methods were used. First, the specific work of rotary tiller was divided into the static specific work and the dynamic specific work. These specific works were calculated and sum of them was used to determine the unknown design parameters of machine. Second, power consumption of rotor was determined based on drawbar force and forward speed of machine.

2.1 Calculation of the rotor power consumption with specific work method

Specific work can be calculated form the following formula[18,19]:

$$A = A_0 + A_B \tag{1}$$

where A is the total specific work of rotor and A_0 and A_B are the static and dynamic specific work, respectively. The A_0 and A_B are determined by using the following relationships:

$$A_0 = 0.1C_0K_0 \tag{2}$$

$$A_B = 0.001a_u.u^2 \tag{3}$$

$$A_B = 0.001a_v.v^2 \tag{4}$$

where V is the tractor forward speed in m/s; u is the peripheral velocity of rotor in m/s; K_0 is the soil specific resistance in kg/dm^3; C_0 is a coefficient proportionate to the soil type and some parameters of machine; a_v and a_u are dynamic coefficients and can be determined by using:

$$a_u = a_v(\frac{u}{v})^2 \tag{5}$$

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

where λ is a proportion coefficient.

2.2 Calculation of the rotor power consumption with drawbar force and machine forward speed method

Drawbar power can be calculated using[1,5]:

$$P_{db} = \frac{V \times D_b}{3.6} \tag{7}$$

$$D_b = \frac{D_a \times a \times b}{1000} \tag{8}$$

where P_{db} is the drawbar power in kW; V is the forward speed in km/h; D_b is the drawbar force in kN; a is the working depth in cm; b is the working width in mm; D_a is the average of the rotary tiller specific resistance in kN that is equal with 21 N/cm^2 for loam and silty-clay-loam soils and 23 N/cm^2 for clay-loam and clay soils.

2.3 Calculation of the tractor maximum work

The maximum work that the rotary tiller can do on the soil must conform to the maximum tractor work. The maximum work of tractor (A_c) is calculated from the following equation[18]:

$$A_c = \frac{7.5N_c\eta_c\eta_z}{V.a.b} \tag{9}$$

where N_c is the tractor power in hp; η_c is the tractor efficiency which is equal to 0.9 for rotation of rotor conform with tractor traveling direction; η_z is the coefficient of tractor power reserve which is between 0.7–0.8; V is the forward speed of tractor in m/s; a is the working depth in dm; b is the working width in dm.

2.4 Calculation of the optimal diameter of rotor

Torque is the most important factor that is affected by the dimensions. Bending moment and weight are neglected because of minuscule value of them[18]. Therefore, selecting the circular cross section for rotor axle and considering the torque, optimal diameter can be determined by the following relationship[18,20]:

$$d = \sqrt[3]{\frac{16M_s}{\tau.\pi}} \tag{10}$$

where d is the optimal diameter of rotor in cm; M_s is the maximum torque at the rotor axle in N.cm; τ is the allowable shear stress at the rotor axle in N/cm^2.

Maximum torque and allowable shear stress at the rotor axle with considering the radius of rotor (R) in mm, yield stress of the base material of rotor (S_y) in MPa, factor of safety ($F.S$), and coefficient of stress concentration (k) because of existence of key emplacement, are determined by using the following equations[20]:

$$\tau = \frac{0.577kS_y}{F.S} \tag{11}$$

$$M_s = K_s \times R \tag{12}$$

$$k_s = \frac{75C_sN_c\eta_c\eta_z}{u_{\min}} \tag{13}$$

where K_s is the maximum tangent forces at the rotor axle in kg; $u_{\min}$ is the minimum linear velocity of rotor in m/s; C_s is the reliability factor that is equal to 1.5 for non-rocky soils and 2 for rocky soils.

2.5 Determination of the optimal working width of rotor

Processes for determination of various parameters of rotor are summarized as follows:

1) Determination of a possible selection domain for V, b, and λ. V domain is selected regarding the common forward speed of tractor for secondary tillage operation. b domain is selected regarding the common working width of the secondary tillage implements. λ domain can be calculated by using the selected V domain and a constant value for u and then from equation (6).

2) Determination of A_0 by using the definite values of C_0 and K_0 and equation (2).

3) Determination of A_B at each of the selected values of V and λ by using equation (3) or (4).

4) Calculation of the specific work of rotary tiller (A).

5) Drawing the A-V diagram for different values of λ by using spreadsheet software such as MS Excel.

6) Determination of the tractor maximum work (A_c) for different values of V by using equation (9) and insert values in the A-V diagram.

7) Determination of design region, which is located under the tractor maximum work curve. At this region, the tractor maximum work is higher than the specific work of rotary tiller.

Applied values of necessary parameters for doing the calculations are presented in the Table 2.

Table 2 Applied values of necessary parameters in the design of rotor

C_o	K_o, kg/dm^2	a, dm	N_C, hp	η_c	η_z	V, m/s	λ	C_s	a_u	R, cm	S_y, MPa	$F.S$	k
2.5	70	1	110	0.9	0.8	0.2-2.8	2-22	2	400	20	520	2	0.75

In order to access to the better selection feasibility, a vast range was exerted for the values of V and λ. Distance among flanges was 24 cm and working width domain was selected as multiplier of this distance as follows:

$$b = (168-192-216-240-264)\text{ cm}$$

Values of specific work of rotary tiller and tractor maximum work are given in Table 3. Additionally, following relations were used to determine the length of sliced soil and rotational speed of rotor[19].

$$L = \frac{2\pi R}{\lambda Z} \tag{14}$$

$$n = \frac{6000 v.\lambda}{2\pi R} \tag{15}$$

where Z is the number of blades on each side of the rotor flange.

Table 3 Values of specific work of rotary tiller and tractor maximum work for different values of *V* and *λ*

$\lambda=u/v$	$av=au(u/v)^2$	V, m/s	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8
2	1600		17.56	17.64	17.76	17.90	18.08	18.28	18.52	18.79	19.10	19.80	20.60	21.60	22.68	23.90	25.24	26.71	28.31	30.04
3	3600		17.64	17.82	18.08	18.40	18.80	19.26	19.80	20.41	21.10	22.68	24.60	26.70	29.16	31.90	34.92	38.23	41.83	45.72
4	6400		17.76	18.08	18.52	19.10	19.80	20.63	21.60	22.68	23.90	26.72	30.00	33.90	38.23	43.10	48.47	54.36	60.76	67.67
6	14400		18.08	18.80	19.80	21.10	22.68	24.55	26.72	29.16	31.90	38.24	45.70	54.40	64.15	75.10	87.19	100.44	114.8	130.40
8	25600		18.52	19.80	21.60	23.90	26.72	30.04	33.88	38.23	43.10	54.36	67.70	83.00	100.44	120.00	141.40	164.95	190.55	218.20
10	40000	A, kg.m/dm^3	19.10	21.10	23.90	27.50	31.90	37.10	43.10	49.90	57.50	75.10	95.90	120.00	147.10	178.00	211.10	247.9	287.90	331.10
12	57600		19.80	22.68	26.72	31.90	38.24	45.72	54.36	64.15	75.10	100.40	130.00	165.00	204.12	248.00	296.28	349.27	406.87	469.08
14	78400		20.64	24.56	30.04	37.10	45.72	55.91	67.68	81.00	95.90	130.40	171.00	218.00	271.50	331.00	396.95	469.08	547.48	632.15
16	102400		21.60	26.72	33.88	43.10	54.36	67.67	83.04	100.44	120.00	165.00	218.00	280.00	349.30	427.00	513.11	607.32	709.72	820.31
18	129600		22.68	29.16	38.24	49.90	64.16	81.00	100.40	122.5	147.00	204.10	272.00	349.00	437.40	536.00	649.76	764.00	893.60	1003.56
20	160000		23.90	31.90	43.10	57.50	75.10	95.90	119.90	147.1	178.00	247.90	331.00	427.00	535.90	658.00	791.90	939.10	1099.10	1271.90
22	193600		25.24	34.92	48.48	65.90	87.20	112.36	141.40	174.31	211.00	296.30	397.00	513.00	644.76	792.00	954.52	1132.63	1326.23	1535.32
	16.8		176.80	117.85	88.40	70.71	58.92	50.51	44.19	39.28	35.35	29.46	25.25	22.10	19.64	17.67	16.07	14.73	13.60	12.62
	19.2		154.68	103.12	77.34	61.87	51.56	41.19	38.67	34.37	30.93	25.78	22.10	19.33	17.18	15.46	14.06	12.90	11.90	11.05
b, dm	21.6	Ac, kg.m/dm^3	137.50	91.66	68.75	55.00	45.83	39.28	34.37	30.55	27.50	22.91	19.64	17.18	15.27	13.75	12.50	11.45	10.57	9.82
	24.0		123.75	82.50	61.87	49.50	41.25	35.35	30.93	27.50	24.75	20.62	17.67	15.46	13.75	12.37	11.25	10.31	9.52	8.84
	26.4		112.50	75.00	56.25	45.00	37.50	32.14	28.12	25.00	22.50	18.75	16.07	14.06	12.5	11.25	10.22	9.37	8.65	8.03

3.1 Determination of the optimal working width of rotor by using the specific works method

Figure 2 was plotted from the data in Table 3 and shows that in forward speed between 0.2 to 1 m/s, tractor maximum work was higher than rotary tiller specific work and only those working width, that are located in this region, are satisfactory for design.

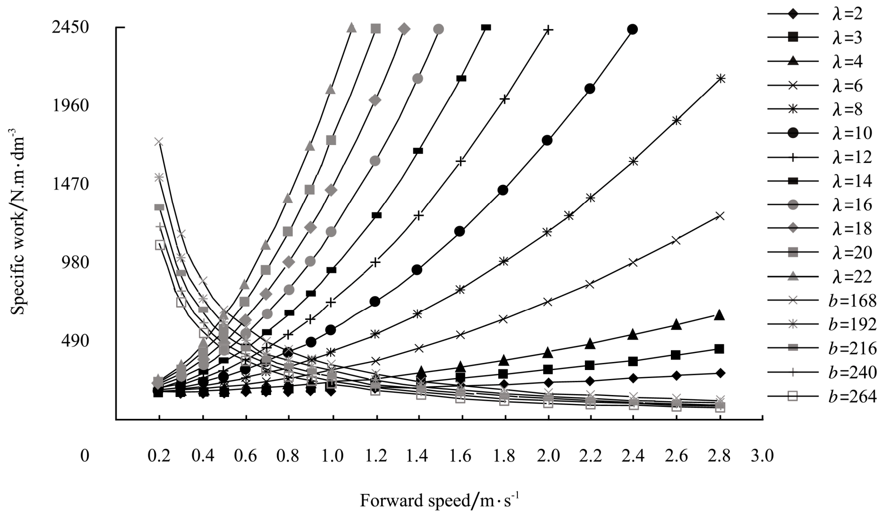

Figure 2 *A-V* curves of rotary tiller and tractor

Working width will be optimal, if difference between the rotary tiller specific work and tractor maximum work are minimum and the rotational speed of rotor and the length of sliced soil are in the satisfying limit. Table 4 shows the possible selections for *L*, *n*, *λ*, and *V* according to the results of Figure 2. Those values of *V* and *λ* of maximum work was higher than rotary tiller specific work and only those working width, that are located in this region, are satisfactory for design.

Table 4 Possible selections for *L*, *n*, *λ*, and *V*

Working width of rotary tiller /cm	(*V*,*λ*)	*n* /r • min^{-1}	*L* /cm	Difference between rotary tiller specific work and tractor maximum work kg.m/dm^3
168	(0.2,22)	210.1	2.85	151.4
	(0.3,22)	315.15	2.85	82.93
	(0.4,22)	420.2	2.85	39.92
	(0.5,22)	525.25	2.85	4.81
	(0.6,16)	458.4	3.92	4.56
	(0.7,12)	401.1	5.23	4.79
	(0.8,10)	382	6.28	1.09
	(0.9,8)	343.8	7.85	1.05
	(1,6)	286.5	10.47	3.45
	(1.2,4)	229.2	15.07	2.74
	(1.4,3)	200.55	20.94	0.65
	(1.6,2)	152.8	31.41	0.5
192	(0.2,22)	210.1	2.85	129.44
	(0.3,22)	315.15	2.85	68.2
	(0.4,22)	420.2	2.85	28.86
	(0.5,20)	477.5	3.14	4.37
	(0.6,14)	401.1	4.48	5.84
	(0.7,10)	334.25	6.28	4.09
	(0.8,8)	305.6	7.85	4.79
	(0.9,6)	257.85	10.47	5.21
	(1,4)	191	15.7	7.03
	(1.2,3)	171.9	20.94	3.1
	(1.4,2)	133.7	31.41	1.5
216	(0.2,22)	210.1	2.85	112.26
	(0.3,22)	315.15	2.85	56.74
	(0.4,22)	420.2	2.85	20.27
	(0.5,18)	429.75	3.49	5.1
	(0.6,12)	433.8	5.23	7.59
	(0.7,10)	334.25	6.28	2.18
	(0.8,8)	305.6	7.85	0.49
	(0.9,6)	257.85	10.47	1.39
	(1,4)	191	15.7	3.6
	(1.2,2)	114.6	31.41	3.11
240	(0.2,22)	210.1	2.85	87.26
	(0.3,22)	315.15	2.85	47.58
	(0.4,11)	420.2	2.85	13.39
	(0.5,16)	382	3.92	6.4
	(0.6,12)	343.8	5.23	3.01
	(0.7,8)	267.4	7.85	5.31
	(0.8,6)	229.2	10.47	4.21
	(0.9,4)	171.9	15.7	4.82
	(1,4)	191	15.7	0.58
	(1.2,2)	114.6	31.41	0.82
264	(0.2,22)	210.1	2.85	87.26
	(0.3,22)	315.15	2.85	40.08
	(0.4,22)	420.2	2.85	7.77
	(0.5,16)	382	3.92	1.9
	(0.6,10)	288.5	6.28	5.6
	(0.7,8)	267.4	7.85	2.1
	(0.8,6)	229.2	10.47	1.4
	(0.9,4)	171.9	15.7	2.32
	(1,3)	143.25	20.94	1.4

tractor maximum work that were higher than the rotary tiller specific work, were selected then by using equations #14 and #15, the amounts of L and n were determined. These calculations can be done either manually or by using a simple computer program. Values of results show that in the working width equal to 240 cm there are suitable limits for forward speed, rotational speed of rotor, and length of sliced soil. In addition, there is minimum difference between tractor maximum work and rotary tiller specific work. Therefore 240, cm is selected as optimal working width for rotary tiller proportionate to MF 399 tractor.

3.2 Validation of rotor working width

In order to validate the gained working width of rotor from previous section, drawbar force and machine forward speed method were used. Considering a value of 240 cm for working width, 1 m/s for forward speed and by using the relation 6, value of drawbar power was obtained as 54.3 kW (73.9 hp). Also, because the equivalent power at the PTO is about 1.16 of drawbar power[21], value of PTO power to operate the rotary tiller was about 62.8 kW (85.8 hp). This value is lower than the maximum power of PTO (see Table 1) Therefore, 240 cm is validated as optimal working width and 1 m/s is obtained as maximum allowable forward speed.

3.3 Determination of optimal diameter

According to the 240 cm for working width, 1 m/s for forward speed and using Table 4, proportional values of λ and L were 4 and 15.7 cm, respectively. From these values, the minimum value of rotor linear velocity was calculated equal to 4 m/s. Table 5 shows the calculated values of the maximum tangent force, maximum torque, and allowable shear stress.

Table 5 Values of the maximum tangent force, maximum torque, and allowable shear stress

K_s /kg	M_s /kN • cm^{-1}	τ/kN • cm^{-2}
27.3	546.3	11.2

According to the results of Table 5 and equation (9), 6.27 cm was calculated as rotor optimal diameter.

4 Conclusion

Optimal working width and optimal diameter of rotary tiller proportionate to the power of MF 399 tractor were determined in order to achieve to the maximum field efficiency of rotary tiller and to minimize the consumed materials in the building of this machine. To this end, energy method was used. Results showed that optimal working width was 240 cm at the 1 m/s as forward speed. Optimal value of rotor’s diameter considering the values of maximum tangent force was determined about 6.27 cm. This paper presents a theoretical method. Therefore, the results of this method must be verified by further tests on a tiller according to the results of this paper.

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