Biblid: 1821-4487 (2013) 17; 3; p 115-119
UDK: 658.2:631.317

Original Scientific Paper
Originalni naučni rad

ENERGY ASPECTS OF THE ROTARY TILLER ROTOR ROTATION DIRECTION IN SOIL TILLAGE

ENERGETSKI ASPEKTI UTICAJA SMERA OBRTANJA ROTORA ROTACIONE SITNILICE PRI OBRADI ZEMLJIŠTA

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ABSTRACT

The aim of this research was to analyze the effects of rotation direction of rotary tiller rotor on the energy expressed as specific work requirement on tractor power take-off (SW_{PTO}). Specific work requirement was measured during field testing. According to the obtained data, the optimal rotor rotation direction was selected based on the working regime and soil condition on the plot. During the operation of rotary tiller with conventional rotor direction, higher specific work requirement was needed for the power of rotary tiller implements through tractor power take-off in comparison to the reverse rotor direction of rotary tiller. The mentioned differences were more noticeable in stubble and soybean fields at lower gears due to the unfavorable physical and mechanical properties of soil and greater presence of vegetation residue. No statistically significant differences were determined on ploughed field. The values of specific work requirement on tractor power take-off (SW_{PTO}) were lower at reverse rotor rotation depending on the change in working speed in comparison to the conventional rotor rotation. Those values on stubble field ranged from 7.0%–23.7%, and on soybean field they ranged from 32.0% to 62.2%. There were no statistically significant differences on ploughed field. The kinematic parameters of rotary tiller, related to the rotation direction, were analyzed in theory and then mathematical expressions were tested on the real values obtained during the field testing. The same trochoides rotated by 180° were observed for both conventional and reverse rotor rotations.

Key words: *energy, rotary tiller, soil tillage.*

REZIME

Cilj rada bila je analiza uticaja promene smera obrtanja rotora rotacione sitnilice na energetski aspekt izražen u vidu specifične angažovane energije na priključnom vratilu traktora (SW_{PTO}). Specifična energija angažovana na priključnom vratilu traktora predstavlja najkompleksniji i nepristrasan parametar na osnovu kojeg se može oceniti uticaj smera obrtanja rotora na količinu angažovane energije po jedinici zapremine obrađenog zemljišta. Specifična angažovana energija izmerena je u poljskim uslovima. U toku ispitivanja, korišćen je obrtni dinamometar, "TD2", mernog opsega do 2 kNm, proizvođača TRCpro, postavljen na izvodu za priključno vratilo traktora, preko kojeg je direktno određen broj obrtaja i obrtni moment na priključnom vratilu traktora. Na osnovu izmerenih podataka izveden je izbor optimalnog smera obrtanja rotora u zavisnosti od režima rada i stanja parcele. Pri radu rotacione sitnilice sa istosmernim obrtanjem rotora angažuje se veća specifična energija za pogon radnih alata rotacione sitnilice preko priključnog vratila traktora u odnosu na suprotnosmerno obrtanje rotora. Navedene razlike su bile više izražene na strništu i na sojištu pri nižim stepenima prenosa i pri nepovoljnijim fizičkim i mehaničkim osobinama zemljišta, kao i pri većem sadržaju biljnih ostataka. Na oranom zemljištu nisu utvrđene statistički značajne razlike. Za suprotnosmerno obrtanje rotora u zavisnosti od promene radne brzine izmerene su niže vrednosti angažovane specifične energije na priključnom vratilu traktora (SW_{PTO}), na strništu od 7,0%–23,7% i na sojištu od 32,0% do 62,2% u odnosu na istosmerno obrtanje rotora. Na oranom zemljištu nisu registrovane statistički značajne razlike. Teorijskom analizom kinematičkih parametara rotacione sitnilice u zavisnosti od smera obrtanja, testirani su matematički izrazi za konkretne podatke izmerene u toku poljskih ispitivanja. Za istosmerno i suprotnosmerno obrtanje rotora uočava se isti oblik trohoide, koje su zarotirane za 180°.

Ključne reči:*energija, rotaciona sitnilica, obrada zemljišta.*

INTRODUCTION

Soil tillage in complex cropping system represents one of the most imprtant agrotechnical measures and it creates conditions which are favorable for growth and development of plants, (*Molnar, 1999*). Soil tillage machines are aimed at turning the ploughing layer of soil, which is exposed to weather conditions, vegetation cover, soil fauna, intensive irrigation and stepping, into a soil where cultivated crops would have optimal conditions for growth and development (*Bajkin, 1994*). Mechanization used for soil tillage has always been a subject of research because around 30% of total energy requirement for soil tillage, and this percentage can be even 50% under difficult conditions, is necessary in the crop production (*Veljić et al., 2008*). In crop production, large amount of energy is needed for soil tillage. Only the irrigation has higher energy input in comparison to soil tillage (*Simbhi et al., 2004*).

Machines attached with implements offer possibility of regulating the working regime which in turn regulates the degree of soil grinding depending on the agrotechnical requirements. Those machines are suitable for the tillage of difficult and wet soils, and they can be used for successful tillage of soils which have high level of moisture and presence of weed (*Páltik et al., 2003*). The choice of appropriate soil tillage in the carrot production had statistically significant influence on the number of plants, quality of root and carrot root yield (*Ponjičan et al, 2009b*; *Bajkin et al, 2010*; *Ponjičan et al, 2012a*). The assessment of rotating implements cannot be based only on the power used but on the soil tillage quality as well (*Marković, 1991*). *Ponjičan et al*, (*2012b*) determined that better quality of soil tillage and low soil degradation can be achieved with reverse rotation of rotary tiller rotor. The aim of this research work was to consider the energy aspect in the analysis of the effect of the change in the direction of rotation of rotary tiller by means of specific work requirement for tractor power take-off. The tests performed on rotary tiller in the field included the change of rotor rotation direction and, based on the calculated values of specific work requirements, optimal rotation direction was determined for specific work regimes and conditions of a plot.

Nomenclature:

a (m) – working depth
B (m) – working width
D (m) – rotor diameter
P_{PTO} – power on PTO
SW_{PTO} (J/m^3) – specific work requirement on PTO
R (m) – rotor radius
CD (-) – conventional rotor rotation direction
RD (-) – reverse rotor rotation direction
t (s) – time
v_m (m/s) – working speed
v_o (m/s) – peripheral velocity
z (-) – number of blades on one side of the flange
λ (-)– indicator of kinematics
ω (s^{-1}) – angular velocity
ωt (work, °) – rotor rotation angle

MATERIAL AND METHOD

The values obtained during the tests on rotary tiller were used to determine specific work requirement on PTO (SW_{pto}) per unit of volume of tilled soil. The investigation of energy related parameters of soil tillage performed by rotary tiller, with both conventional and reverse rotation directions, was conducted under field conditions, in the vicinity of Kisač village. The type of soil was chernozem.

The tests were performed on three different types of field, with respect to the first crop and previous type of tillage:

- on stubble field,
- on soybean field, and
- on ploughed field.

The rotary tiller was adjusted with a built-in invertor for the purpose of assessing the influence of rotation direction of rotary tiller rotor on the power parameters (Fig. 1).

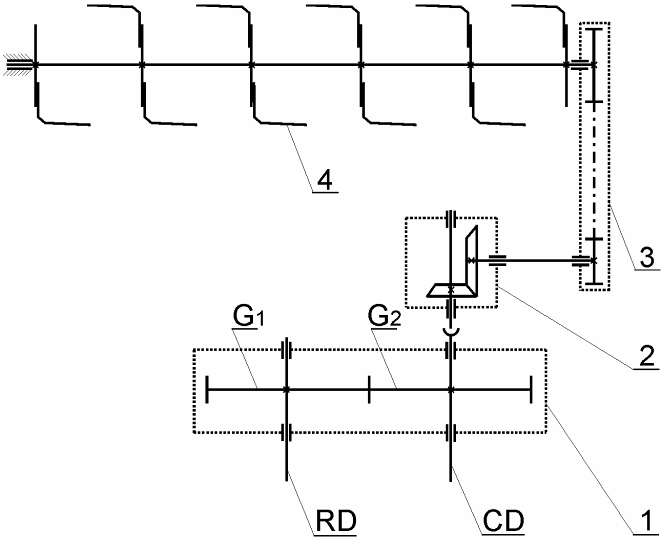


Fig. 1. Kinematic scheme of power transmission in the adjusted rotary tiller (Ponjičan, 2011):
1-invertor with connection for PTO for conventional rotation direction (CD) and reverse rotation direction (RD);2-reduction with cone gears; 3-reducion with chain transmission; 4-rotor with blades

Invertor is made of two gears, each having 50 teeth (G_1 and G_2), which is why there are no changes in the transmission ratio. Two grooved shafts for the connection of cardan shaft are located on the invertor. By connecting the cardan shaft to the left PTO, viewed in the direction of machine motion, the rotary tiller has the same direction of rotor rotation as the tractor wheels, which is the so-called conventional direction of rotation (CD). By connecting the cardan shaft to the right PTO the rotation direction shanges and it becomes reverse rotation direction (RD). The rotary tiller and tractor were connected according to the standards (*ISO 730/II1979(E); JUS M.L1.013:1998; ISO 5673-2:2005*).

During the field-testing of energy related parameters, the methodology and measuring equipment were those of the accredited Laboratory for power machines and tractors, Department of Agricultural Engineering at the Faculty of Agriculture in Novi Sad. The Laboratory for power machines and tractors was accredited according to standard *JUS ISO/IEC 17025:2001* by *JUAT* Accreditation body from Serbia, Belgrade and *OECD* Paris. Measuring of number of revolutions and torque was performed by dynamometer "*TD2*" with a measuring range of up to 2 kNm, produced by TRCpro, Serbia. Based on the values obtained, the specific work requirement per volume unit of tilled soil ($SW_{PTO,}$ J/m^3) was calculated for both rotor rotation directions.

Numerous authors were interested in the theoretical analysis of kinematic parameters of rotary tiller *(Radomirović at al, 2006, 2008; Celik and Altikat, 2008*), and the equations for more or less accurate calculation of kinematic parameters can be found in literature. It was necessary to determine the following parameters in order to do the analysis: trajectory of blade's tip and kinematic indicator λ. The differences between conventional and reverse rotor rotation were determined based on the known work parameters (working speed, working depth and kinematic indicator), design related parameters (rotor diameter and number of blades on rotor), and by applying the formed mathematical equations for kinematic and geometric parameters.

Trajectory of blade's tip

When tillage of soil is performed by a rotary tiller, tip of the blade has complex trajectory which can be straight (transmission) and reverse (relative). Parametric equations of the trochoide which shows the tip of the blade of rotary tiller in the given coordinate system (Fig. 2) are:

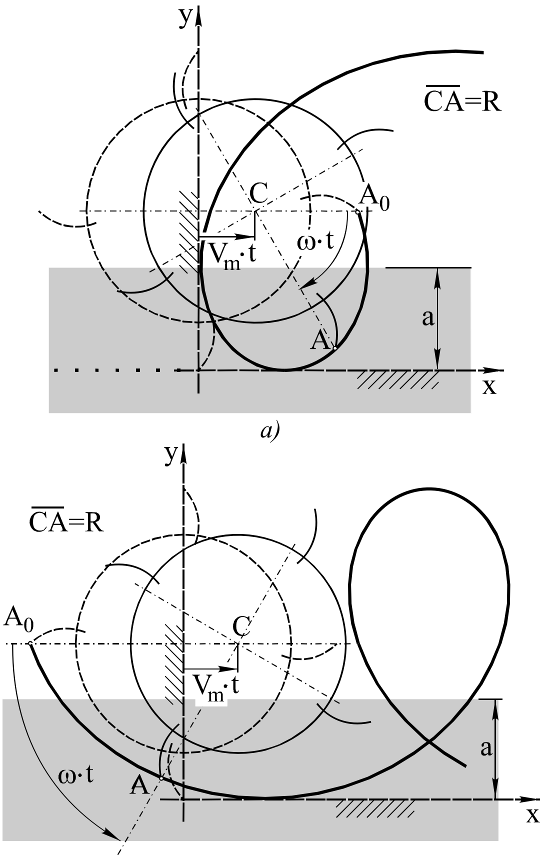
$$x(t) = v_m \cdot t \pm R \cdot \cos \omega t\,, \tag{1}$$

$$y(t) = R - R \cdot \sin \omega t \tag{2}$$

In the equation, for the tip of the blade in the direction of x-axis for conventional rotor rotation direction sign "+" is used, and for reverse rotor rotation direction sign "–" is used. The trajectories of the blade's tip are presented in Figure 2.

At the initial point of time the blade's tip position is in point A_0. At provisional point of time t, the tip of the blade is in the point A, when the angle of rotor is ωt (Fig. 2).

In case of reverse rotor rotation, the trajectory of tip of the blade is in such a position that the working part of tip of the blade (trochoide) is on the opposite side, and this allows the use of kinematic indicator and rotary tiller in a considerably wider range.



a)

b)

Fig. 2. Trajectory of tip of the blade (Radomirović et al., 2006): a) at conventional rotor rotation direction; b) at reverse rotor rotation direction

Kinematic indicator

Kinematic indicator of rotary tiller operation (λ) is defined as a ratio between peripheral velocity (v_o) and working speed (v_m):

$$\lambda = \frac{v_o}{v_m} = \frac{R \cdot \omega}{v_m} \tag{3}$$

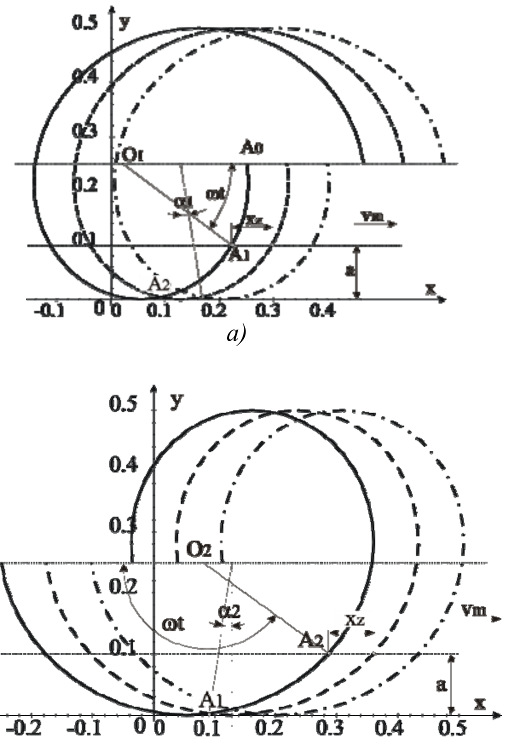
RESULTS AND DISCUSSION

Analysis of kinematic parameters of rotary tiller with respect to the rotor rotation direction

After the kinematic parameters of rotary tiller, related to the rotation direction, were analyzed in theory, the mathematical expressions were tested on the real values obtained during the field testing. In field, the adjusted rotary tiller was used and its working width was B = 1.3 m, rotor diameter was D = 0.50 m and the number of blades concentrated on one side was z = 3. With constant value of angular velocity ω = 16.038 s^{-1} the working speed ranged from v_m = 0.29–1.08 m/s. The set working depth was a = 0.1 m.

Trajectory of blade's tip

The trajectories of tips of three adjacent blades located on the same shaft were determined by using the parametric equations (1 and 2) for the working speed value v_m = 0.55 m/s (Fig. 3).



a)

b)

Fig. 3. Trajectories of the blade's tip (Ponjičan, 2009a): a) at conventional rotor rotation direction; b) at reverse rotor rotation direction

According to Figure 3, the trochoides for both conventional and reverse rotation direction had the same shape. After changing the rotor rotation direction, the trochoides turned for 180° (*Radomirović et al, 2006*). The working width of blade x_z, which had same values for starting data regardless of the direction of rotation and working depth, could also be determined according to the figure.

The angle of rotor rotation ωt at the point of blade's cutting into the soil during conventional rotation (A_1), and at the point of blade's exit from soil (A_2) primarily depends on the working depth a and rotor radius R (Fig. 3).

During the operation of rotary tiller the analysis was done on the starting parameters which were peripheral velocity, kinematic parameter, working width of the blade and working depth, and it was concluded that the selection of values for working speed ranging from 0.29 m/s to 1.08 m/s was adequate and that those values enabled complete, comprehensive consideration of kinematic working regime of the tested rotary tiller (*Matjašin et al., 1988; Páltik et al., 2003*). During the testing rotor revolutions per minute were 153.23 min^{-1}, and the value of 4.001 m/s for peripheral velocity was constant. The indicated value was within the recommended limits for the operation of rotary tiller under the optimal working regime (*Matjašin et al, 1988*). The values of kinematic indicator ranged from 13.8 to 3.7. Kinematic parameter value had to be higher than $\lambda \geq 3$, which was the condition for successful soil tillage (*Páltik et al, 2003*).

Specific work requirement on tractor power take-off

According to the ratio between the power on tractor power take-off (P_{PTO}) and working speed (v_m), working width (B) and working depth (a), specific work requirement on tractor power take-off (SW_{PTO}) was calculated per volume unit of tilled soil. Specific work requirement on tractor power take-off represents the most complex objective parameter which is used for the assessment of influence of rotor rotation direction on the amount of specific work requirement per unit of volume of tilled soil (*Ponjičan et al.,* 2011).

The *F*-test of analysis of variance at the significance treshold of 5% showed that there were statistically significant differences between conventional and reverse rotor rotation on stubble and soybean fields, and that there were no statistically significant differences on the ploughed field. The tests showed that under different conditions the specific work requirement on PTO decreased with an increase of working speed.

Duncan's test, with a significance threshold of 5%, showed that the values of specific work requirements on PTO at both conventional and reverse rotor rotation were statistically different on stubble and soybean fields (Tab. 1). Those differences occurred at working speed of up to 0.43 m/s on stubble field, while on soybean field they occurred at working speed of up to 0.77 m/s. There were no statistically significant differences on ploughed field.

Table 1. Specific work requirement on tractor power take-off with respect to the rotor rotation direction under different plot conditions but on the same type of soil (Ponjičan, 2009a)

Working speed, m/s	Rotor rotation direction	Stubble field, kJ/m^3	Soybean field, kJ/m^3	Ploughed field, kJ/m^3
0.29	Conventional	296.4 f	–	–
	Reverse	239.5 e	–	–
0.43	Conventional	236.6 e	345.6 d	112.0 a
	Reverse	213.2 d	213.0 ab	112.2 a
0.55	Conventional	210.5 cd	295.4 c	108.0 a
	Reverse	192.9 ac	202.8 ab	107.0 a
0.77	Conventional	186.4 a	246.9 bc	97.5 c
	Reverse	174.3 a	187.1 a	95.6 c
1.08	Conventional	153.7 b	177.7 a	85.9 b
	Reverse	154.0 b	167.0 a	83.0 b

*Comparison by Duncan's test (α = 5%) was done per columns and not rows.

On stubble field, depending on the working speed, higher specific work requirement on tractor PTO was recorded with conventional rotor rotation in comparison to the reverse rotor rotation and it ranged from 7.0–23.7% . On soybean field, with conventional rotor rotation the recorded values were higher by 32.0–62.2% with respect to the reverse rotor rotation of rotary tiller. Depending on the testing conditions, homogeneity of soil and working speed, the obtained values for specific work requirement on tractor PTO ranged from 83.0kJ/m^3 on ploughed field, for the working speed of 1.08 m/s and with reverse rotor rotation, up to 345.6 kJ/m^3 on soybean field, for the working speed of 0.43 m/s and with conventional rotor rotation. The F-test of analysis of variance and Duncan's test at the significance treshold of 5% showed that, on stubble and soybean fields, rotary tiller with conventional rotor rotation had higher specific work requirement on PTO compared to the reverse rotor rotation in lower gears, on soils with less favorable physical and mechanical properties, and with greater presence of vegetation residue. On ploughed field, no statistically significant differences were observed. Higher working speed decreased specific work requirement on PTO (SW_{PTO}), which was in accordance with the results provided by Matjašin et al, (1988); Páltik et al, (2003) and Kheiralla et al, (2004). With higher working speed the volume of tilled soil incrases more with respect to the power (P_{PTO}), so the specific work requirement on PTO (SW_{PTO}) decreases (*Salokhe and Ramalingam, 2001, 2003*).

By applying the nonlinear polynomial regression, mathematical dependences of specific work requirement on PTO with respect to the working speed (equations 4-9) were determined, as well as the coefficient of determination (R^2).

Stubble field CD:

$$y = 23.276x^2 - 49.837x + 42.314 \qquad R^2 = 0.8536 \qquad (4)$$

Stubble field RD:

$$y = 10.591x^2 - 24.043x + 29.313 \qquad R^2 = 0.7363 \qquad (5)$$

Soybean field CD:

$$y = 20.977x^2 - 57.431x + 54.796 \qquad R^2 = 0.8288 \qquad (6)$$

Soybean field RD:

$$y = 5.632x^2 - 16.005x + 27.01 \qquad R^2 = 0.712 \qquad (7)$$

Ploughed field CD:

$$y = 2.1867x^2 - 7.8733x + 14.401 \qquad R^2 = 0.4013 \qquad (8)$$

Ploughed field CD:

$$y = 2.2732x^2 - 8.301x + 14.8 \qquad R^2 = 0.4998 \qquad (9)$$

The influence of rotor rotation direction was evident in stubble and soybean fields in spite of big differences in soil properties, which resulted in low values of coefficient of determination (for stubble field R^2 = 0.74-0.85; for soybean field R^2 = 0.71-0.83 and for ploughed field R^2 = 0.40-0.50) (Fig. 4).

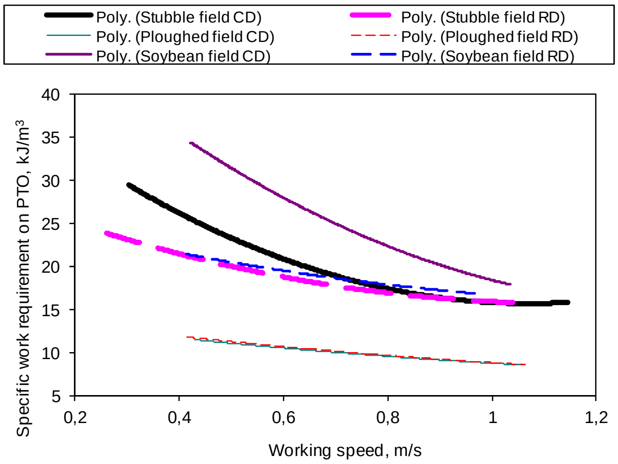


Fig. 4. Curves showing specific work reuirement on tractor PTO depending on the working speed and testing conditions (Ponjičan 2009a)

Figure 4 shows second degree polynomials for specific work requirement on tractor PTO according to the equations obtained by nonlinear polynomial regression (*Ponjičan, 2009a)*. The biggest differences between the values of specific work requirement on tractor PTO were obtained for different testing conditions (stubble, soybean and ploughed fields) and with different working speeds. Also, the direction of rotary tiller's rotor rotation is an important factor which should be considered when assessing the specific work requirement per volume unit of tilled soil.

CONCLUSION

The analysis and choice of rotor optimal kinematic parameters were done for the adjusted rotary tiller which was tested in field conditions. The working speed ranged from 0.29 m/s to 1.08 m/s and it enabled comprehensive consideration of kinematic working regime of the tested rotary tiller. The values of kinematic parameters ranged from 13.8 to 3.7 whereat the value of kinematic parameter had to be higher than $\lambda > 3$. Energy related parameters of the rotary tiller at different rotor rotation directions were tested under different conditions (stubble, soybean, and unploughed fields) and on the same type of soil. Specific work requirement on PTO represents the most complex and objective parameter for the assessment of the influence of rotor rotation direction on the amount of work requirement per unit of volume of tilled soil. F-test of analysis of variance and Duncan's test with the significance threshold of 5% showed that rotary tiller with conventional rotor rotation had higher specific work requirement (SW_{pto}) on tractor PTO for the power of rotary tiller implements when compared to the reverse rotor rotation of rotary tiller. The discovered differences were more noticeable on stubble and soybean fields at lower gears, with unfavorable physical and mechanical properties of soil and higher number of plant remains. There were no statistically significant differences observed on ploughed field.

ACKNOWLEDGMENT: The research presented in this paper was financed by the Ministry of Education, Science and Technological Development, Republic of Serbia. Grant no. TR 31046 and TR 31058, 2011-2014.

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Received: 25.3.2013. Accepted: 12.4.2013.