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EFFECT OF CUTTING SPEED AND DEPTH ON THE COURSE OF RESULTANT FORCE ACTING ON A CULTIVATOR TINE

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ABSTRACT

The paper presents research results on the effect of cutting depth and speed on the resultant force tilt angle and location of its application point on a flexible tine ended with a cultivator point. The studies were carried out in field conditions in sandy clay with the gravimetric moisture of 11.2% and volumetric density of 1470 kg·m^{-3}. Tines whose flexibility coefficient was 0.0061; 0.0711; 0.0953 and 0.1406 m·kN^{-1} were used. It was found out that that the resultant force tilt angle raises at the increase of the cutting speed and drops at the increase of depth but this angle and its gradient at the increase of the cutting depth grow along with the decrease of the flexibility coefficient of tines. The increase of the cutting speed and depth causes the decrease of both the distance of the resultant force application point on the tool from the bottom of a furrow and a proportion of this parameter to the cutting depth. The courses of the distance of the resultant force application point on the tool from the bottom of a furrow and courses of proportion of this parameter to the cutting depth as the function of cutting do not differ significantly for tines with higher flexibility coefficients while for the most rigid tine values of these parameters and their gradients are higher. All obtained courses of the analysed values as a function of depth and cutting speed were described with regression equations.

Introduction

Work and energy consumption of treatments in technologies applied in the field plant production may be obtained mainly due to limitation and simplification of cultivation treatments (Chen et al., 2005; Pabin et al., 2007). Despite this limitation and simplification, cultivation treatments must meet the specific agrotechnical requirements (Przybył et al., 2009; Talarczyk et al., 2011). It causes that in the applied tools and multi-function cultivation aggregates elements with not only low working resistance but also with high intensity of effect on soil should be applied. Many authors claim that the proportion of the cutting resistance to the intensity of effect on soil is a basic factor which defines utility values of the tool (Godwin, 2007), but this intensity is frequently defined with the scarification quality index (McKyes and Maswaure, 1997). Flexible tines are cutting elements which characterize the advantageous proportion of the working resistance to the intensity of effect on soil (Berntsen et al., 2006). The presented advantages cause that flexible tines are used not only in traditional cultivators with a low demand for towing power but also in modern multifunctional cultivation aggregates which require the use of high power tractors.

Flexible tines ended with a cultivator point are a narrow soil cutting tool. Issues related to the effect of such tools on soil are solved with analytical methods (Onwualu and Watts, 1998; Godwin, 2007) based mainly on Godwin's and Spoor's model (1977) and at the use of final elements method (Topakci et al., 2010; Ucgul et al., 2014). However, such solutions are related to stiff elements and focus mainly on issues related to loading of tools and soil deformation zones (Piotrowska, 2003; Ucgul et al., 2014). Empirical research, whose object are narrow spring elements relate to a similar issue.

Difficulties in the analysis of research results of flexible tools result mainly from dynamic relocation and changes in the geometry which take place under the influence of variable loads. Correct analysis of the effect of such tools on soil next to the previously presented issues also requires knowledge on the parameters of setting the resultant force (Onwualu and Watts, 1998; Godwin, 2007) i.e. the tilt angle and the application point on a tool. The value of the first mentioned parameter (proportion of the vertical force to the horizontal force) may result directly from small number of investigations, where vertical forces acting on tools were included (Wheeler and Godwin, 1996; Onwualu and Watts, 1998; Ucgul et al., 2014; Godwin and O'Dogherty, 2007). However, this parameter was not directly analysed. On the other hand, the effect of various parameters which determine the cutting process on the location of the application point of the resultant force has not been yet analysed for spring tools and in case of rigid tools was assumed arbitrarily without empirical confirmation.

Location of the resultant force application point is provided as a proportion of the distance of this point from the bottom of a furrow to the cutting depth. According to Bernacki (1981) this proportion is 0.5 for the harrow tine while for stiff tines of a cultivator ended with a cultivator point – 0.2. In case of a plough, Kuczewski (1981) assumes various values of this parameter which are 1/3 or 0. The last value means that the resultant is applied at the blade of a ploughshare. On the other hand Friedman (1973) assumes this value as 0.5 for a firmer similarly to Bernacki (1981) for tine harrow elements.

The objective of the research was to determine the effect of depth and speed of cutting soil with a cultivator tine on the tilt angle of the resultant force direction and the application point on the tool including the changes of the tine flexibility.

Methodology of research

Values necessary to determine the tilt angle of the resultant force and the point of its application on the tool require simultaneous registration of components of the vertical and horizontal resultant force, moment of force and temporary cutting depth (Lejman et al., 2015). These values were measured with the use of a stand for measurement of forces acting on the soil cutting tools in field conditions, equipped with a multiaxis power converter and the system for measurement of a temporary depth of operation of a tool. A stand and its description were presented in the paper by Owsiak et al., (2006). Measured values were registered with the frequency of 1000 Hz.

The investigations were carried out in soil with a granulation of sandy clay, in which participation of particular groups of fractions determined pursuant to PTG 2008 was: gravel – 4%, sand – 67%, dust – 18% and loam – 11%. Gravimetric moisture content, its compactness, volumetric density and cutting resistance along with standard deviations of measurements provided in brackets were respectively: 11.2% (0.5%); 600 kPa (70 kPa); 1470 kg·m^{-3} (30 kg·m^{-3}) and 44 kPa (8 kPa). Parameters which characterize soil were determined in 10 iterations according to the applicable standards and recommendations by ASABE (2006). Before starting the research, soil was ploughed to the depth of 30 cm and then in order to uniform it was scarified with a rototiller and compacted with rollers deep and on the surface.

The object of the studies consisted in four s-shaped spring cultivator tines ended with a cultivator point with the width of 0.045 m, radius of curvature R-0.17 m and with the rake angle, determined in a static state of 40º. These tines, due to the introduced structural modifications differed with the values of the flexibility coefficient. These coefficients were statically determined with the use of a testing machine Instron 5566 and their values for tines determined in the further part of the paper as Z1, Z2, Z3 and Z4 were respectively 0.0061; 0.0711; 0.0953 and 0.1406 m·kN^{-1}. The presented coefficients define horizontal relocation of the cultivation point under the effect of load. At the same time, during calibration, no significant value of vertical relocation of the cultivation point within the range of force values, which took place during field research, was reported.

Tests were carried out in two series. In the first series, the effect of the cutting speed on the parameters of setting the resultant force, and in the second series - the effect of depth was determined. In the first series for which a constant cutting depth was assumed and which was 12 cm, speeds were 1; 1.7; 2.4 and 3 m·s^{-1}. In the second series at the constant cutting speed (3 m·s^{-1}), cutting depths were be 6, 8, 10 and 12 cm. In each series, particular measurements were carried out in two independent iterations. Since, the cutting depth is one of factors which affect the recorded sizes the most significantly (horizontal force, vertical force and the moment of force) in the first series only these fragments of courses of recorded values were selected for which depth was 12 cm ± 0.5 cm. Including the recorded values only for the assumed range of depths was possible due to correlation with them during the measurement of a temporary cutting depth. In case of determination of the effect of cutting depth, the obtained temporary courses of depth in time were divided into equal ranges where the average value was assumed as a present cutting depth. Therefore, in calculations of parameters of resultant force setting, also the remaining values registered in the determined ranges for which the average cutting depth was assumed were included.

The tilt angle of the resultant force (β) was determined from the proportion of its component forces - horizontal (F_x) and vertical (F_y). The distance of application points of the resultant force on the tool from the bottom of a furrow (s) was computed based on the value of the force momentum (M), resultant force (F), momentary cutting depth (a) and momentary location of the cultivation point based on the loading value and flexibility coefficient. A detailed methodology of selecting the ranges of selected values and methodology of determination of the application point of a force in a tool including calculation algorithms and visualization of the calculation results were presented in the paper by Lejman et al., (2015).

Research results

The effect of the soil cutting speed (v) with tines of various values of the flexibility coefficient (Z1-Z4) on the tilt angle of the resultant force (β), distance of the force application point from the bottom of a furrow (s) and proportion of this distance to the cutting depth ($s \cdot a^{-1}$) were presented in figures 1-3 and the effect of the cutting depth (a) on these parameters were presented in figures 4-6.

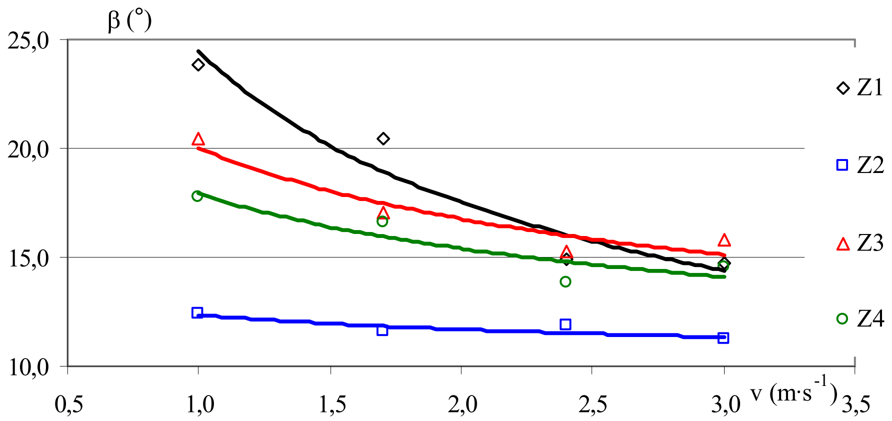

Figure 1. The effect of cutting speed (V) on the tilt angle of the resultant force (β) with tines (Z1 – Z4) on various flexibility

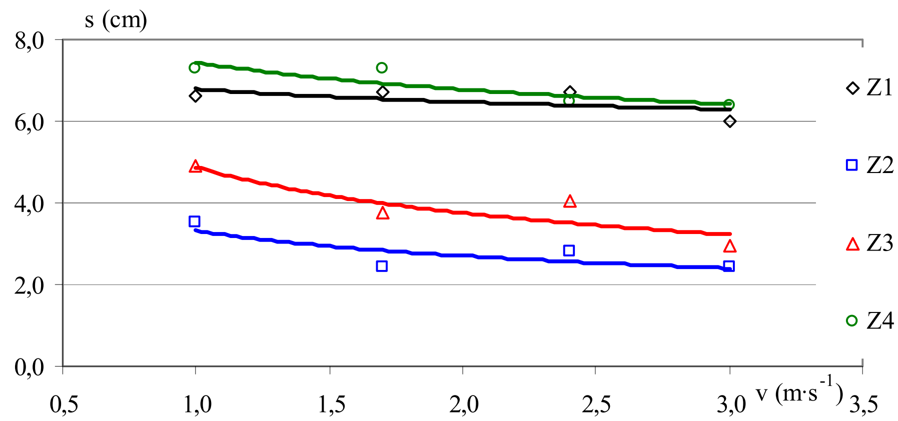

Figure 2. The effect of the cutting speed (v) with tines (Z1-Z4) of varied flexibility to the distance of the application point of the resultant force on the tool from the bottom of a furrow (s)

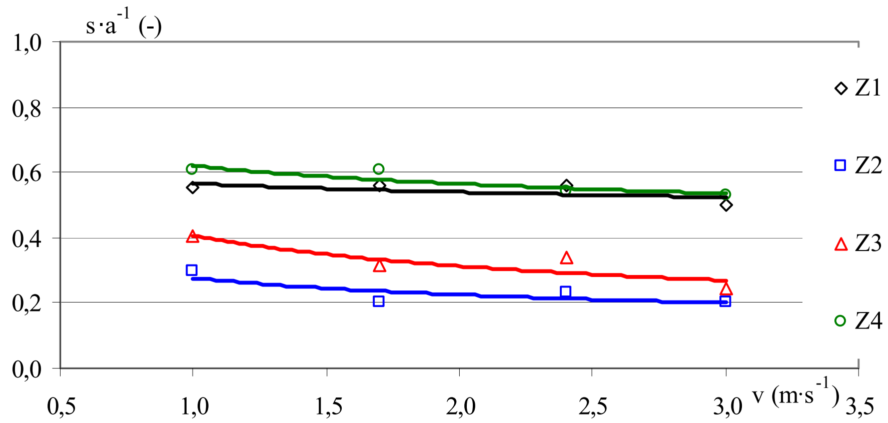

Figure 3. The effect of the cutting speed (v) with tines (Z1-Z4) of varied flexibility on the proportion of the distance of the resultant force application point on the tool from the bottom of a furrow (s)

Values of all calculated parameters which characterize the location of the resultant force (β, s i $s \cdot a^{-1}$) decrease with the increase of the speed which may be described with power equations. Coefficients (c) and (b) of these equations and correlation coefficients were presented in table 1. The decrease of the tilt angle value of the resultant (β) is confirmed in the Wheeler's and Godwin's research (1996) which confirmed no effect of the speed on the vertical force value at the simultaneous increase of the horizontal force acting on narrow tools.

The highest values of the angle (β) and the highest gradients of their decrease at the increase of the speed were reported for a tine with the lowest flexibility, in case of which also the highest significance of correlation was reported. It suggests that the increase of the tine cutting speed, which may be recognized as constant causes higher increases of the horizontal component of the resistance than the vertical component. On the other hand, Z2 tine has the lowest values of the angle (β) and the gradient which has its consequences in the lowest significance of correlation. Except this tine, the remaining have similar values of the angle (β) at the speed of approximately 3 $m \cdot s^{-1}$.

The cutting speed does not explicitly affect the distance of the resultant force application point from the bottom of a furrow (s) and proportion of this distance to the cutting depth ($s \cdot a^{-1}$), which was presented in figures 2 and 3. Only in case of tines Z3 and Z4 correlation is significant at the lowest possible level of significance α=0.2 (table 1). At the constant cutting depth which is 12 cm distance (s) is within 2 to 8 cm. The biggest distances occur in case of cutting with a tine which has the highest flexibility (Z4) but no explicit effect of elasticity of the remaining tines on the value of these parameters was reported since the distance decreases in the following order Z1, Z3 i Z2.

Table 1.
Equations describing the effect of the cutting speed (v) on the tilt angle of the resultant force (β), distance of the resultant force application point on the tool from the bottom of a furrow (s) and the proportion of this distance to the cutting depth ($s \cdot a^{-1}$) and the equations coefficient values (c) and (b)

Tine	$\beta = c \cdot v^b$			$s = c \cdot v^b$			$s \cdot a^{-1} = c \cdot v^b$		
	c	b	R	c	b	R	c	b	R
Z1	24.46	-0.48	0.96***	6.79	-0.07	0.60	0.57	-0.07	0.60
Z2	12.34	-0.08	0.86*	3.32	-0.29	0.78	0.28	-0.29	0.78
Z3	20.02	-0.26	0.95**	4.88	-0.38	0.87*	0.41	-0.38	0.87*
Z4	17.91	-0.22	0.90**	7.44	-0.13	0.89*	0.62	-0.13	0.89*

Correlation significant for the level of probability: *** $\alpha = 0.05$, ** $\alpha = 0.10$, * $\alpha = 0.20$

The previously described tendencies result in no explicit effect of the cutting speed on the proportions of distance (s) to the cutting depth (a) because in case of analysis of the speed effect constant depth was applied. It is reflected in the same values of exponents of equations, correlations and the significance of correlation. Proportion (s) to (a) changes only at cutting with tines of various flexibility and is within ca. 0.2 to ca. 0.6 but the nature of the effect of elasticity of tines on this parameter is identical as in case of the distance from the bottom of a furrow.

The increase of cutting depth causes the increase of the resultant tilt angle which may be described with logarithmic equations regardless the elasticity of tines (table 2). The increase of the angle (β) at the increase of the depth may be explained with two-direction soil deformation zones, which occur at exceeding the critical depth, which may result in a higher increase of the vertical force in comparison to the horizontal force increase. It was found out that the values of the angle (β) and their gradients decrease at the increase of elasticity of tines. It results from a higher deflection of a more flexible tine and thus its rake angle which determines the location of the border of various soil deformation zones (Godwin and Spoor, 1977). It may result also in insignificant correlation of the angle (β) and cutting depth which occurs in case of a tine with higher elasticity. In case of this tine, one may hypothetically assume that the increase of this lead angle as a result of rake is so high that causes three-direction soil movement. In case of the remaining tines, correlation is significant at the level of α=0.05. The presented analysis suggests that the highest vertical stability and penetration ability was in case of tines with higher rigidity, which results from lower effect of resistance on the increase of the rake angle of these tools.

The distance of the resultant force application point from the bottom of a furrow and the proportion of the distance of this point to the cutting depth decreases at the increase of the cutting depth (figure 5 and 6) which may be described with power equations. It may be noticed that the courses of the analysed parameters (s i $s \cdot a^{-1}$) do not differ explicitly for tines, which may be recognized as flexible tines. Tine (Z1), which may be recognized as rigid, because the value of its coefficient of elasticity is lower than the order of magnitude than the remaining ones (Z2, Z3 i Z4), has a higher value than those parameters and their gradient.

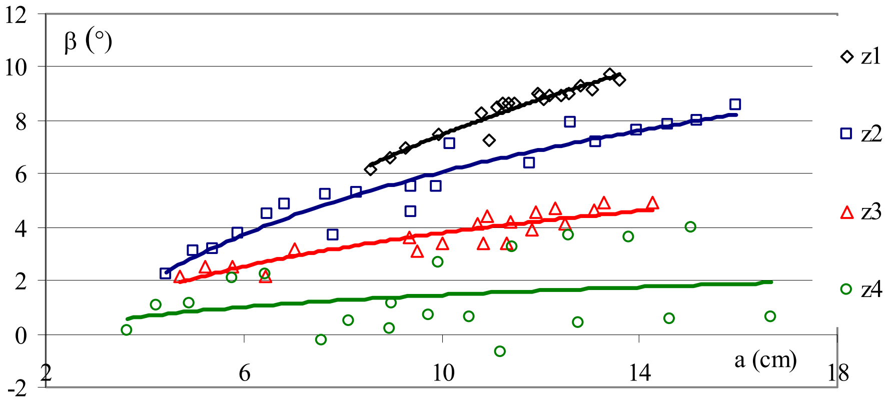

Figure 4. The effect of cutting speed (V) on the tilt angle of the resultant force (β) with tines (Z1-Z4) with various flexibility

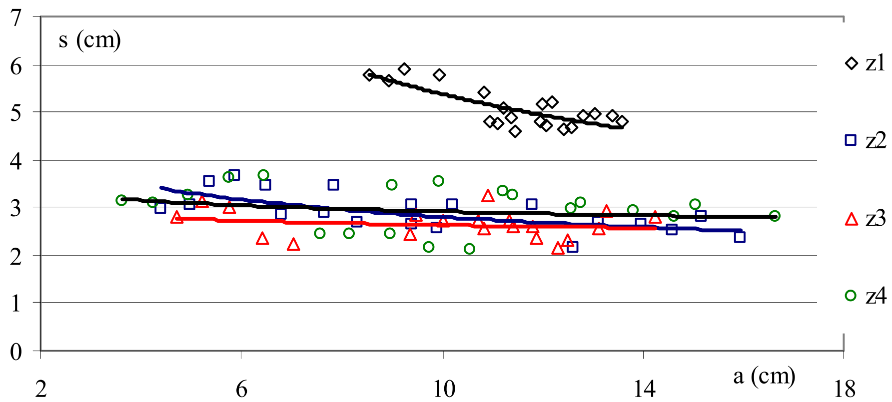

Figure 5. The effect of the cutting speed (v) with tines (Z1-Z4) of varied elasticity to the distance of the application point of the resultant force on the tool from the bottom of a furrow

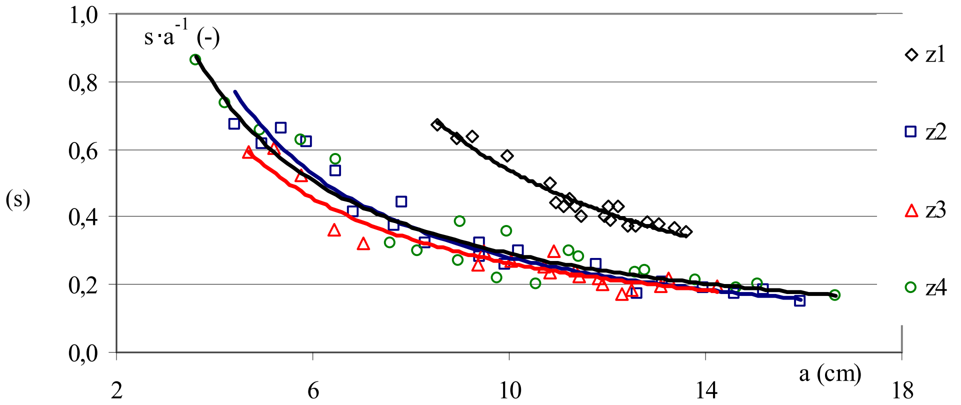

Figure 6. The effect of the cutting speed (v) with tines (Z1-Z4) of varied elasticity on the proportion of the distance of the application point of the resultant force (s) to the cutting depth (s)

Table 2.
Equations describing the effect of the cutting speed (v) on the tilt angle of the resultant force (β), distance of the resultant force application point on the tool from the bottom of a furrow (s) and the proportion of this distance to the cutting depth ($s{\cdot}a^{-1}$) and the equations coefficient values (c) and (b)

Tine	$\beta = c \cdot Ln(a) - b$			$s = c \cdot a^b$			$s{\cdot}a^{-1} = c \cdot a^b$		
	c	b	R	c	b	R	c	b	R
Z1	7.34	-9.44	0.96***	15.8	-0.47	0.78***	15.8	-1.47	0.97***
Z2	4.60	-4.53	0.95***	4.82	-0.23	0.67***	4.82	-1.23	0.98***
Z3	2.45	-1.87	0.90***	3.09	-0.07	0.21*	3.09	-1.07	0.96***
Z4	0.88	-0.57	0.27	3.54	-0.05	0.22*	3.54	-1.08	0.94***

Correlation significant for the level of probability: *** $\alpha = 0.05$, ** $\alpha = 0.10$, * $\alpha = 0.20$

The values of the proportion of distance (s) to the cutting depth (a) which were reported (figure 3 and 6) are a surprise for authors because they considerably exceed the values previously presented in the literature review. It is clearly visible especially for small cutting depths. The existing fact may be explained by the phenomenon of soil elevation over the tool (Piotrowska, 2003; Ucgul, 2014),which causes that actual distance of the upper soil layer from the bottom of a furrow during cutting is higher than the depth of operation which takes place in the agrotechnical aspect.

Conclusions

1. The tilt angle of the resultant force acting on the flexible tine of a cultivator rises at the increase of the cutting speed and drops at the increase of depth which may be described respectively with power and logarithmic equations.

2. The tilt angle of the resultant force and its gradient at the increase of the cutting depth rise along with the decrease of the flexibility coefficient of tines which suggests that tools with higher rigidity have better penetration ability and vertical stability.
3. The increase of the cutting speed and depth cause the decrease of both the distance of the resultant force application point on the tool from the bottom of a furrow and a proportion of this parameter to the cutting depth, which may described with power equations.
4. The course of the distance of the application point of the resultant force on the tool from the bottom of a furrow and courses of proportion of this parameter to the cutting depth as the function of cutting do not differ significantly for tines with higher flexibility coefficients while for a rigid tine values of these parameters and their gradients are higher.
5. Bigger proportions of the distance of the resultant force application point on the tool from the bottom of a furrow to the cutting depth than the ones assumed in literature may be explained with a higher real depth of cutting caused by soil elevation in front of the tool.

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WPŁYW PRĘDKOŚCI I GŁĘBOKOŚCI SKRAWANIA NA PRZEBIEG SIŁY WYPADKOWEJ DZIAŁAJĄCEJ NA ZĄB KULTYWATORA

Streszczenie. Przedstawiono wyniki badań wpływu głębokości i prędkości skrawania na kąt nachylenia siły wypadkowej i położenie jej punktu przyłożenia na sprężynowym zębie zakończonym redliczką. Badania przeprowadzono w warunkach polowych w glinie piaszczystej o wilgotności 11,2% wag. i gęstości objętościowej 1470 $kg \cdot m^{-3}$. Stosowano zęby o współczynnikach sprężystości 0,0061; 0,0711; 0,0953 i 0,1406 $m \cdot kN^{-1}$. Stwierdzono, że kąt nachylenia siły wypadkowej rośnie przy wzroście prędkości skrawania i maleje przy wzroście głębokości, przy czym kąt ten i jego gradient przy wzroście głębokości skrawania rosną wraz ze spadkiem współczynnika sprężystości zębów. Wzrost prędkości i głębokości skrawania powodują spadek zarówno odległości punktu przyłożenia siły wypadkowej na narzędziu od dna bruzdy, jak i proporcji tego parametru do głębokości skrawania. Przebiegi odległości punktu przyłożenia siły wypadkowej na narzędziu od dna bruzdy i przebiegi proporcji tego parametru do głębokości skrawania w funkcji głębokości skrawania nie różnią się istotnie dla zębów o wyższych współczynnikach sprężystości, natomiast dla zęba o największej sztywności wartości tych parametrów i ich gradienty są wyższe. Wszystkie uzyskane na podstawie badań przebiegi analizowanych wielkości w funkcji głębokości i prędkości skrawania opisano równaniami regresyjnymi.

Słowa kluczowe: gleba, sprężynowy ząb kultywatora, siła wypadkowa