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METHODOLOGICAL ASPECTS OF DETERMINATION OF RESULTANT FORCE ACTING ON THE CULTIVATOR SPRING TINES

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ABSTRACT

This paper presents aprocedure for determination of the tilt angle of the resultant force and the point of its application on the cultivator-spring tine. These parameters include the temporary value of horizontal and vertical force, moment of force and cutting depth. Numerical methods were applied to determine the point of application of the resultant force as an intersection point of the resultant force direction and the circuit described on the cultivator point curvature. Calculation algorithms include changes in the position and geometry of the cutting system caused by a dynamical load of a tool. Tests were carried out in field conditions in the sandy clay of 11.2% density moisture. Two depths of cutting with four tines, which differ with flexibility coefficients, were applied. It was stated that the setting parameters of the resultant, calculated with the use of the presented method, have low-value standard deviations. It was also found out that the tine flexibility and cutting depth positively influence the tilt angle of the resultant and the tine flexibility affects only the distance of the point of the resultant force application on a tool from the bottom of a furrow.

Introduction

Reduction of the field plant production costs and consequently the increase of competitiveness of the manufactured products create a need to lower the energy and labour consumption as early as on the stage of soil cultivation treatments. It is obtained mainly byintroduction of simplified cultivation technologies and partial or complete rejectionof the most energy consuming treatment, namely plough (Chen et al., 2005; Talarczyk and Zbytek, 2006). Thus, one may notice the increase of users' interest in cultivating tools, including springtine cultivators, which in the Polish conditions are still used as independent tools or their working elements comprise multi-functional cultivating aggregates. Moreover, the increase of the intensity of the research studies on the impact of these tools on soil may be observed (Sahu and Raheman, 2006; Przybył et al., 2009; Lejman et al., 2013).

Understanding the mechanisms of impact in the system comprising a cutting element and soil is significant on the stage of design and production, as well as on the stage of exploitation of tools (Godwin and O’Dogherty, 2007). According to Topacki et al., (2010) a correct analysis of stresses in the cutting element may lead to reduction of its weight and the increase of its strength and consequently may lowerthe production costs. A precise analysis of stresses requires, however, knowledge not only on the values of acting forces but also on their courses.

Cultivator tines ended with a cultivator point are narrow cutting elements whose working depth is higher than their width. In such case, it is assumed that soil may move in three directions, i.e. to the front, up and to the sides.It was confirmed by theoretical analyses and the research (Onwualu and Watts, 1998; Piotrowska, 2003; Godwin, 2007). The presented results of theoretical analyses and empirical research refer to narrow tools mounted stiff to the machine. These results can not be applied directly to tools mounted in a flexible manner, in case of which the values of forces, which change during cutting, cause their elastic strain and as a result change the cutting parameters and geometry of the cutting system.

A great majority of empirical tests on flexible soil cutting elements focused mainly on the issue related to determination of the force value (Berntsen et al., 2006; Lejman et al., 2011). However, there are no complex tests which would also include analysis of the resultant force course (Onwualu and Watts, 1998; Godwin, 2007) whose determination requires the measurement of the force moment value. Additional impediment manifests in the fact that correct determination of parameters of the resultant force course may be flawed by a high amplitude of the force in comparison to the average value, which even in the ideal laboratory tests conditions may exceed 20%, which is justified with inertia changes of the moved soil and possible occurrence of the periodical cutting (Berntsen et al., 2006; Godwin and O'Dogherty, 2007). Failure to include temporary changes of the cutting depth, which take place during measurements, particularly carried out in field conditions, may also influence the errors in determination of both parameters of the resultant force course andthe component forces values, because, according to many authors, even small changes of depth cause great changes of tools loading (Godwin, 2007). This fact is significant for testing the tools which operate on smaller depths, for which a proportion of the cutting depth amplitude to the assumed depth may be significant.

The objective of the research studies was to develop a procedure for determination of the parameters of the resultant force course influencing thecultivator spring tine ended with a cultivator point with temporary values of loads and depth of work. An additional objective of the paper was to verify the developed method consisting in determination of the significance of the cutting depth and the tine flexibility impact on the determined parameters of the resultant force courses.

Method of determination of parameters of the resultant force course and testing methods

Parameters which define the explicit location of the resultant force acting on the soil cutting tool are the tilt angle of this force from the level and its application point on a tool. Determination of these parameters requires the knowledge on the component forces of horizontal and vertical forces, the moment of force and temporary cutting depth, which, as it was presented above, determines the tool loading and a position of the application point of the resultant force. In case of flexible tools, it is significant to determine also a temporary position of a tool, which changes in relation to the load.

Values required for calculations, were recorded with the use of a stand presented in the paper written by Owsiak et al., (2006) which were equipped with the recording system of the temporary depth of work. Depth changes during measurements were correlated with the remaining recorded values because the relieved sensor wheel moves in front of the tools on the same route, which causes that the recorded temporary depth of work is moved in time. Method of this correlation, which includes the distance of the wheel axis and the cutting speed, was presented in the previously quoted paper by Owsiak et al., (2006).

Exemplary courses of the cutting depth (a), horizontal force (F_x) and vertical force (F_y) and the moment of force (M) were presented in figure 1. The figure presents also the method of determination of the range of the forces value and the moment for the exemplary assumed cutting depth of 12 cm. For the assumed average value of depth, this method includes its ranges within ± 0.5 cm and the force and the moment values are calculated as an average of the ranges. This method allows averaging fast-changing courses of forces caused by self-incited vibrations of a tool (Niyamapa and okhe, 2000; Duerinckx, 2005). Each course of the recorded sizes is defined by a high frequency and amplitude, which is particularly visible in case of the vertical force (fig. 1). Such averaging enables thus, determination of various cutting parameters and parameters of a tool (cutting depth and velocity, flexibility and geometry of a tool) omitting disorders caused by fast-changing own vibrations.

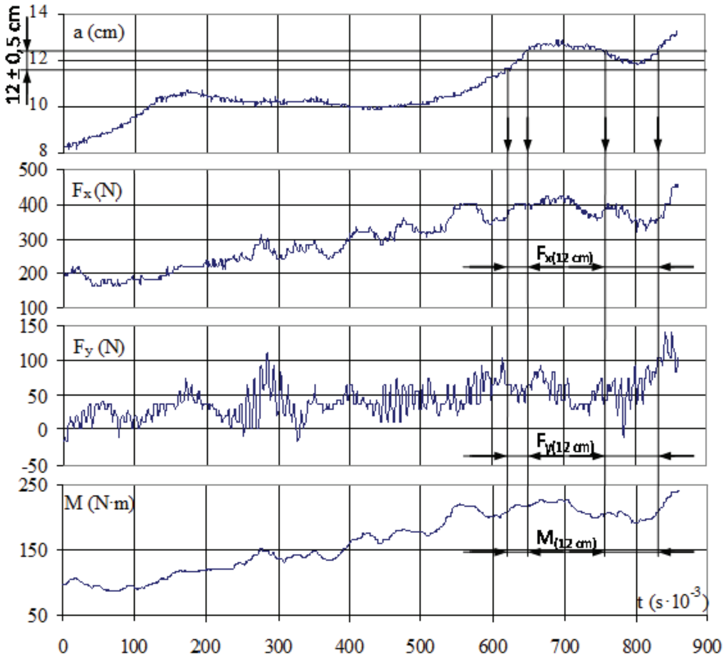

Figure 1. Exemplary courses of the cutting depth (a), horizontal force (F_x), vertical force (F_y) and the moment of force (M) are correlated in time (t) and the method of determination of the particular values ranges for the depth of 12 cm

The tilt angle of the resultant force towards the level (β) is determined directly from the horizontal force value (F_x) and the vertical force value (F_y) assuming that the vertical force is positive when it is directed downwards:

$$tg\beta = \frac{F_y}{F_x}(\text{-}) \tag{1}$$

Determination of the point of application of the resultant force requires the use of the artificial bases method. A force transducer mounted on the stand is a base element. A schematic representation of the measurement system with the mounted cultivator spring tine was presented in figure 2. The reference point on the transducer was determined with coefficient 0:0. It is also a point, towards which the system of measurement of the force moment was calibrated. In case of the non-loaded S-shaped spring tine ended with a cultivator point with the width of 0.045 m and the curvature radius R=17 cm of the distance from the cultivator point to the reference point were determined (xs_R) and (ys_R). Under the influence, the cultivator point bow moves horizontally by the value of (Δx_R) which depends on the tine flexibility and the value of the operating force.

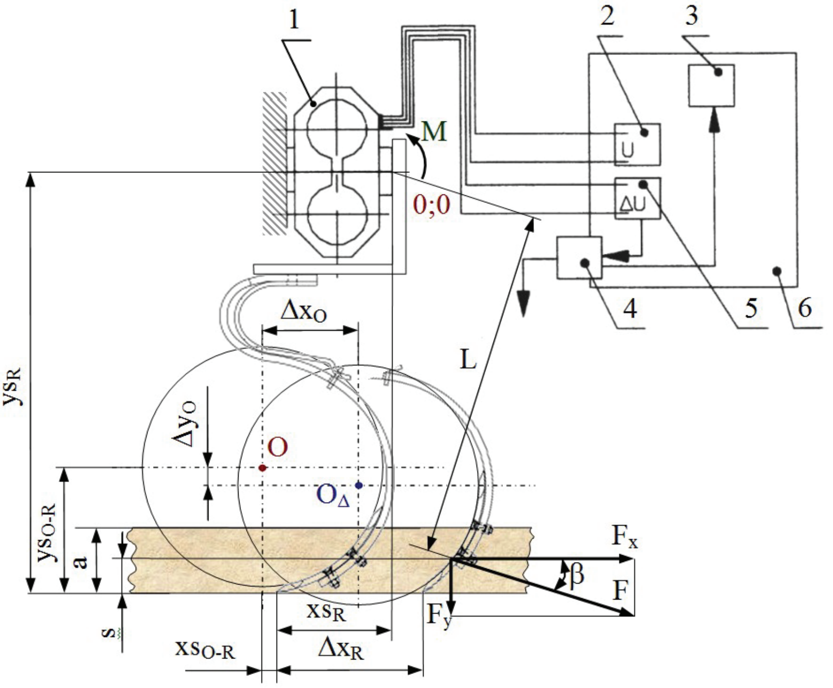

Figure 2. Schematic representation of the measurement system with the mounted cultivator tine: 1 – multi–axis force transducer, 2 – highly–stabilized power supply, 3 – memory module, 4 – computer interface, 5 – measurement system of power, 6 – data collector. The remaining symbols were described in the text

Determination of the value of this parameter requires statistical calibration of tines in order to calculate the value of their flexibility modulus (k_x). After they are calculated, a horizontal movement (Δx_R) may be calculated from the following formula:

$$\Delta x_R = k_x \cdot F(\mathrm{cm}) \tag{2}$$

where:

k_x – flexibility coefficient, ($\mathrm{cm \cdot N^{-1}}$)

F – tine load, (N)

Because, during calibration of tines, no significant impact of the load on the vertical movement of the cultivator point was reported, it was assumed that the value (Δy_R) equals zero.

Coordinates of the circle centre (O), described on the curvature of the unloaded cultivator point,are displaced in respect to the point by ($xs_{O\text{-}R}$) and ($ys_{O\text{-}R}$). After loading the cultivator point, the centre of the circle described on its curvature, moves to the position (O_Δ), whose ordinate and abscissa, in the coordinate system presented in figure 2 and 3, may be described with formulas 3 and 4:

$$xO_\Delta = xs_R + k_x \cdot F - xs_{O-R} - \Delta O_x \cdot k_x \cdot F \text{ (cm)} \tag{3}$$

$$yO_\Delta = ys_R - ys_{O-R} + \Delta O_y \cdot k_x \cdot F \text{ (cm)} \tag{4}$$

where:

ΔO_x – a coefficient that corrects horizontal displacement of the circle centre as a result of changes in the cultivator point geometry, (-)

ΔO_y – a coefficient that corrects the vertical displacement of the centre of the circle as a result of changes in the cultivator point geometry, (-)

Equation of the circle with the centre placed in the point whose coordinates are expressed with the formulas 3 and 4 has the following form:

$$(x - xO_\Delta)^2 + (y - yO_\Delta)^2 = R^2 \tag{5}$$

The point of application of the force on the tool is in the intersection point of the circle described with the equation (5) with the direction of the resultant force operation, whose equation has the following form:

$$y = a \cdot x + b \tag{6}$$

The equation (6) slope (a) may be calculated as follows:

$$a = \frac{F_y}{F_x} \tag{7}$$

and the absolute term (b):

$$b = L \cdot cos\beta + \frac{F_y}{F_x} \cdot L \cdot sin\beta \tag{8}$$

where:

L –arm of the resultant force operation (cm).

The arm of the resultant force operation (L) may be determined based on the recorded momentary values of the moment of force (M) and the components of the horizontal (F_x) and vertical force (F_y):

$$L = \frac{M}{\sqrt{{F_x}^2 + {F_y}^2}} \text{ (cm)} \tag{9}$$

When the relations (7), (8) and (9) are included, the equation (6) takes the following form:

$$x = \frac{F_y}{F_x} \cdot x + \frac{M}{F_x} \tag{10}$$

The point of application of the resultant force on the tool, is in the intersection point of the circle described with the equation (5) and the straight line (10). Coordinates of the intersection point (x_P) and (y_P) were determined with the numerical methods in the MS Excel spreadsheet, where the results of simulations were visualized in the system of coordinates x, y (fig. 3). Since the system of equations formed from the relations (5) and (10) has two solutions, the results, for which the coordinate (x_P) is higher than (xO_Δ), were included. The distance of the point of application of the force on the tool from the bottom of a furrow (s) is a difference between the distance of the cultivator point bow in the vertical plain and the reference point (ys_R) and the determined ordinate of the intersection point of the circle and the direction of the resultant operation (y_P).

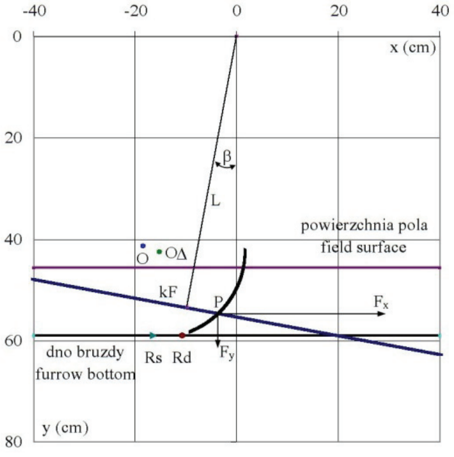

Figure 3.Visualization of the tilt angle (β) of the direction of the resultant force operation (kF) and its point of application on the tool (P) and the position of the cultivator point in the static system (Rs) and after loading (Rd). The remaining symbols were described in the text

Testing of this method for determination of the tilt angle of the resultant resistance and the point of its application on the tool was carried out by measurement in field conditions in soil with granulation of sandy clay according to PTG of 2008. Average mass humidity of soil was 11.2% and its bulk density and compactness were respectively 1470 $kg \cdot m^{-3}$ and 600 kPa. The object of the research consisted of four S-shaped cultivator, spring tines which due to the introduced modifications, had varied flexibility coefficients. Values of these coefficients were determined on the testing machine Instron 5566 and for tines marked with z1, z2, z3 and z4 were respectively 0.0061; 0.0711; 0.0953 and 0.1406 $m \cdot kN^{-1}$.

The measurement of the horizontal and vertical force, the moment of force and temporary cutting depth were carried out in two independent iterations. It was assumed that the measurements were carried out at two cutting depths – 8 and 12 cm and the speed of 1 $m \cdot s^{-1}$. From the recorded courses of the work depth variability, the ranges 7.5 to 8.5 cm and 11.5 to 12.5 cm were selected according to the previously presented methodology (fig. 1). For analysis of results the multi-factor analysis of variance with iterations type 4x2 and the uniformity test of groups at the level of significance of $\alpha=0.05$ were applied.

Results of tests

When testing the presented method of determination of the resultant force courses, it was assumed that on account of various values of flexibility of tines, and thus various changes of geometry of the cutting system, significant changes of the determined parameters of course will occur. It was also expected that both the assumed method of selection of the momentary cutting depth ranges and including a correction of the momentary position of the cultivator point and its geometry, which are dynamically changing during cutting, will allow obtaining the results which are defined by repeatability of the calculated values.

Results of calculations of the tilt angle of the resultant force of resistance (β) and the distance of its point of application to the bottom of a furrow (s) carried out in two iterations were presented in table 1. A general tendency to the decrease of the angle (β) and distance (s) value at the increase of the flexibility of tines, regardless the cutting depth may be noted. Increase of the cutting depth results in the increase of the angle (β) regardless its flexibility. Such tendencies cannot be observed in case of the impact of depth on the distance of the point of application (s). Differences in the obtained results described with the presented tendencies are confirmed by the tests results of the analysis of variance presented in table 2 and 3, which on the assumed level of significance prove that the value of angle (β) influences significantly both the flexibility of tines as well as cutting depth, and the distance of the point of application (s) influences only the flexibility. Moreover, it was stated that a significant interaction of the cutting depth and the flexibility of tines takes place only in case of the distance of the point of application (s).

Making comparison of the results of calculations carried out based on two iterations of measurements, it was stated that standard deviations of the tilt angle of the resultant of resistance values (β) are within 0.07° to 1.98° and the distance of the point of application of the resultant force on the cultivator point to the bottom of a furrow (s) are within 0.00-0.71 cm. It should mentioned then, that upper limits of standard deviations of the calculated parameters have very low values and in case of distance (s) the value of this deviation is lower than the admissible fluctuation of the cutting depth of cultivation tools.

Table 1

Results of calculations of the tilt angle of the resultant force (β) and the distance of its point of application to the bottom of a furrow (s)

Tinetype	Depth (cm)			
	8		12	
	β (°)	s (cm)	β (°)	s (cm)
Z1	6.1	5.8	8.9	5.2
	7.5	5.8	9.0	4.8
Z2	5.3	2.7	7.9	2.1
	5.2	2.9	6.4	3.1
Z3	3.2	2.3	4.1	2.3
	3.6	2.4	4.7	2.2
Z4	0.5	2.5	0.4	3.1
	-0.3	2.4	3.2	3.2

Table 2

Results of analysis of variance factors on tilt angle of resultant force

Variability force	Degrees offreedom	F Value	Level ofsignificance
Flexibility of tine	3	43.585	0.0001
Depth	1	13.776	0.0059
Flexibility of tine x depth	3	0.295	0.8281

Table 3

Results of analysis of variance factors on distance of point of application of resultant force

Variability force	Freedom degrees	F Value	Level ofsignificance
Flexibility of tine	3	103.570	0.0001
Depth	1	0.516	0.5004
Flexibility of tine x depth	3	4.903	0.0321

Based on the test of uniform groups, it was found out that non-uniform groups at the significance of their impact on the tilt angle of the resultant force constitute the levels of the cutting depth (8 and 12 cm) and the levels of flexibility of tines (z1-z4). In case of the impact of the levels of the analysed factors on the distance of the point of application of the resultant force, both levels of cutting depth belong to the uniform group, and the levels of flexibility of tines may be included to two uniform groups. It was found out that the first one includes a tine, whose flexibility is similar to the flexibility of the stiff tine and is lower by one value than the flexibility of the remaining tines, which belong to the second group.

Conclusion

The presented method of determination of the setting parameters of the resultant force acting on the cultivator spring tine consists in calculation of the tilt angle of the resultant force and the point of its application on a tool. These parameters are determined based on the temporary values of the horizontal and vertical force, the moment of force and cutting depth. The calculation includes the values and moments of forces, for which deviation of the registered cutting depth is ± 0.5 cm. The artificial bases method, where positions and geometry of the cutting system resulting from deviation of the previously statistically calibrated tines, was corrected dynamically, was used for calculations. The point of application of the resultant force was indicated as an intersection point of the direction of the resultant force and the circuit described on the cultivator point curvature. Numerical methods including visualization of the determined parameters in the x, y system were used for calculations.

Based on the tests carried out in field conditions in sandy clay, it was found out that the setting parameters of the resultant have low-value standard deviations. It was also found out that the flexibility of a tine and cutting depth influence the tilt angle of the resultant force and only the flexibility of a tine significantly affects the distance of the point of application of the resultant force on the tool from the bottom of a furrow.

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METODYCZNE ASPEKTY WYZNACZANIA PARAMETRÓW PRZEBIEGU SIŁY WYPADKOWEJ DZIAŁAJĄCEJ NA SPRĘŻYNOWE ZĘBY KULTYWATORA

Streszczenie. Przedstawiono metodę wyznaczania kąta nachylenia siły wypadkowej i miejsca jej przyłożenia na sprężynowym zębie kultywatora. Parametry te obliczane są z uwzględnieniem chwilowych wartości sił poziomej i pionowej, momentu siły i głębokości skrawania. Punkt przyłożenia siły wypadkowej wyznaczano metodami numerycznymi jako miejsce przecięcia kierunku działania siły wypadkowej i okręgu opisanego na krzywiźnie redliczki. W algorytmach obliczeniowych uwzględniono zmiany położenia i geometrii układu skrawającego spowodowane dynamicznym obciążeniem narzędzia. Badania testacyjne metody przeprowadzono w warunkach polowych w glinie piaszczystej o wilgotności wagowej 11,2%. Stosowano dwie głębokości skrawania czterema zębami różniącymi się współczynnikami sprężystości. Stwierdzono, że obliczone przy użyciu przedstawionej metody parametry ustawienia wypadkowej charakteryzują się małą wartością odchyleń standardowych. Stwierdzono również, że sprężystość zęba i głębokość skrawania wpływają istotnie na kąt nachylenia wypadkowej, natomiast na odległość punktu przyłożenia siły wypadkowej na narzędziu od dna bruzdy wpływa istotnie tylko sprężystość zęba.

Słowa kluczowe:gleba, sprężynowy ząb kultywatora, siła wypadkowa