

Kinematic analysis of rotary harrows

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Abstract

This article presents the kinematic analysis of the tine motion of a rotary harrow. In particular, it analyses the trajectories that the tines describe when they are pulled by the motion of the tractor and rotated by the rotors. This analysis, has led to the identification of the parameters that influence the motion of the tines and how these parameters intervene in the secondary tillage. The interaction between the tines and the soil is evaluated considering a plastic soil, i.e. without any cleavage and its propagation. With this hypothesis, the dimensions of the soil clods created by the passage of the tines in the soil have been analysed. The trajectories described by the tines of the machine, and therefore the dimensions of the portions of worked or unworked soil, are influenced by the operating parameters of the soil tillage process, such as the tractor speed and the angular speed of the tines themselves. Furthermore, a contribution is also given by the geometric parameters of the machine, such as the rotor radius and the geometric configuration of the rotary harrow in terms of rotor arrangement. This study is based on the creation of a mathematical model of the trajectories of the tines of a rotary harrow during soil tillage. The model is parametric and makes it possible to simulate and optimise the tillage process. The approach adopted also makes it possible to visualise the trajectories in graphic form for an easy visual interpretation of the results.

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Introduction

In agriculture, tools connected to a tractor are commonly used for soil cultivation. These can simply be carried or pulled by the tractor, as in the case of a plough. However, there are some tillage tools that, in addition to being pulled, are powered by the tractor's power take-off (PTO), such as the rotary harrow. Agricultural tillage implements powered by PTO use this mechanical power to operate its own tools in order to carry out soil tillage. This category includes: rotary tillers, spading machines and also rotary harrows. Rotary harrows are used in secondary tillage, typically preceded by ploughing, for refinement and levelling of the soil. They are also used for inter-row processing for the purpose of weed control in vineyards and orchards. Soil tillage is achieved by the movement of rotating parts, called tines or knives, sunk into the soil. The final quality of the soil processing depends on many factors related to the physical properties of the soil such as texture, structure, bulk density, porosity and soil moisture (Cavazza, 1981). Other contributing factors are the shape of a tine and its inclination and speed with respect to the soil (O'Callaghan and McCullen, 1965; Godwin, 2007). The influence of speed in the soil-tool interaction in terms of the force exchanged with the soil is presented in (Stafford, 1979; Swick and Perumpral, 1988).

In the literature, the most widespread articles are based on the study of the plough and of the rotary tiller (Hirasawa *et al.*, 2013; Ahmadi, 2017), while the contributions concerning the rotary harrow are rarer (Piccarolo, 1976). In Chan *et al.* (1993) the effect of the combination of pulling speed and rotor speed is studied by measuring the physical properties of the soil, while (Destain and Houmy, 1990) investigates the effects on soil porosity. A first approach to the study of the harrow-soil interaction has been addressed by the authors in Raparelli *et al.* (2018, 2019).

This work analyses the kinematics of the rotary harrow, considering both the angular speed of the tines and the pulling speed imposed by the tractor. The study, based on the motion laws of the rotary harrow, analyses the influence of these parameters on the trajectories of the harrow tines. In terms of tine-soil interaction, only the tracks left by the tines are taken into account, under the plastic soil hypothesis. A further objective of the work is to optimise the tillage process by tackling the criticalities found in the previous analysis. In this perspective, new and innovative rotary harrow solutions have been analysed, in order to reduce processing times and limit fuel consumption, while at the same time ensuring optimum levels of soil processing.

Materials and methods

Rotary harrow

Figure 1A and B show two diagrams that clarify the geometry and the components of the system under examination. The

analysed harrow consists of a rigid frame (1) arranged parallel to the ground and with the longitudinal axis perpendicular to the travelling direction of the tractor. The frame, see Figure 1A, houses a series of gears (2), which engage with each other transmitting motion to the rotors. A pair of cutting elements (3) is fixed to each of them, see Figure 1B, arranged in opposition to each other. There is also a speed reducer (4) that receives the motion, via the joint (5) and a cardan shaft, from the tractor PTO.

Motion law of the cutting elements

The absolute speed of the tine is composed of two elements: the pulling speed v_t due to the tractor and the relative speed imposed by the rotation ω of the rotors. Considering a Cartesian reference system x, y , in which axis x represents the tractor's travel direction, the motion law expressed in terms of coordinates x, y is:

$$\begin{cases} x_I = v_t \cdot t + r \sin(\omega \cdot t) \\ y_I = r \cos(\omega \cdot t) \end{cases} \quad (1)$$

in which t represents time, r the distance of the tine from the axis of the rotor, v_t the pulling speed e ω the rotor's angular speed.

Equation (1) represents the Cartesian coordinates of the trajectory covered by an individual tine. Considering the case of a rotor consisting of two tines in opposition of phase, the trajectory of the second tine is described by the following Cartesian coordinate system:

$$\begin{cases} x_{II} = v_t \cdot t + r \sin(\omega \cdot t + \varphi) \\ y_{II} = r \cos(\omega \cdot t + \varphi) \end{cases} \quad (2)$$

in which φ represents the phase shift angle. It is worth noting that the equations represent prolate trochoid curves (Raparelli *et al.*, 2019).

These equations have been used to build a numerical model which makes it possible to analyse the paths of tines mounted on a rotary harrow. The model created is of the parametric type and makes it possible to change the geometrical characteristics and the operating parameters of the harrow. The parameters that can be changed are: i) number of rotors; ii) position of the rotors; iii) wheelbase between the rotors; iv) number of tines per single rotor and related phase shift angles; v) distance of the tines from the axis of the rotor; vi) tractor speed; vii) angular speed of the rotors.

The software developed has been used to analyse the types of rotary harrows currently used in agriculture, consisting of a series of counter-rotating rotors arranged along a row orthogonal to the tractor direction of motion. The pulling speed v_t corresponds to the tractor travel speed, the rotation speed of the rotors ω is imposed by the angular speed ω_{PTO} of the tractor's PTO and the transmission ratio i is characteristic of the speed reducer, which is located between the PTO shaft and the rotors.

In order to carry out an assessment of the soil quality, it is useful to define objective parameters for analysing the trajectories. For this purpose, the geometric dimensions of the clods of worked soil have been identified as parameters. In particular, two different types of clods have been identified: the first type, called first cut or primary clods, is the one that is observed for tractor speed equal to the speed limit. The second type, called secondary clods, has been obtained following a further delimitation of the primary clods. The primary clods are characterised with the parameters x_1 and y_1 , while the secondary plates with x_2 and y_2 . See Figure 2 for a graphic interpretation of these parameters. Other parameters have also been considered in the analysis: the average speed v_m of the tine

and the total length of the trajectory L_t . The average speed v_m has been evaluated as the ratio between L_t and the time taken to travel it. The evaluation of the work quality has been carried out by evaluating the size of the soil clods as the tractor speed v_t varied. In order for the simulations to be comparable to each other, they have been carried out with the same total length of the trajectories of the tines L_t and with a constant average speed v_m . The tests have been replicated for multiple average speeds v_m .

Results and discussion

Influence of the tractor speed v_t

The evaluation of the effect of the tractor speed v_t on the characteristics of the path of the tines in the soil is of considerable importance, being predominantly the only parameter that can be changed by the operator during the tillage soil. Figure 3 shows the trajectories, covered by a single rotor equipped with two opposed tines,

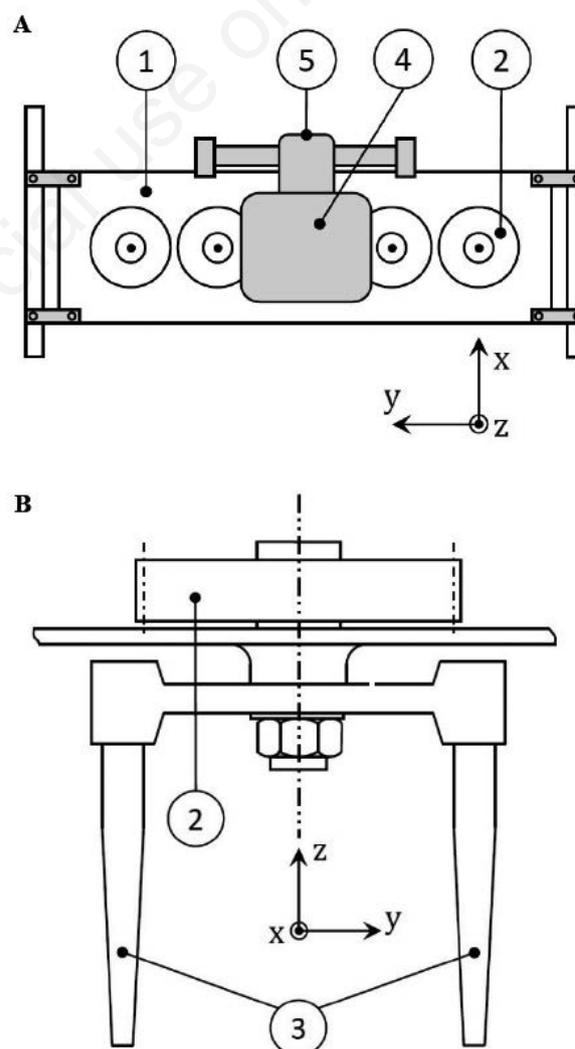


Figure 1. A) Top view of a schematic rotary harrow, (1) rigid frame, (2) gears, (4) speed reducer, (5) cardan shaft joint. B) Frontal view of the elements present in a rotor, (2) gear, (3) cutting elements or tines.

evaluated with different tractor speeds v_t and a constant PTO angular speed ω_{PTO} . Furthermore, the tracks represent the trajectories developed by five complete rotor rotations. It is shown that, as the tractor speed v_t increases, the trajectories are completed with an advancement x of the tractor proportional to the speed v_t , therefore the area of processed soil increases. In the present work, we identify as limit speed the tractor speed v_t at which, all things being equal, the trajectories described by the tines of the same rotor are tangent to each other like those corresponding to the speed $v_t = 4.65$ km/h in Figure 3. In this condition, clods of worked soil are always formed as a surface enclosed and/or circumscribed by the trajectories. For speeds lower than the limit speed, it is possible to observe an overlap of the trajectories of the tines of the same rotor. This overlapping phenomenon is not observed at speeds higher than the limit speed. There are therefore areas of soil that have not been affected by the passage of the knives, see Figure 3. The tractor motion speed v_t therefore influences the distribution of the trajectories on the surface of the soil, *i.e.* the passage of the knives in the soil. The final quality of the soil processing is therefore influenced by v_t .

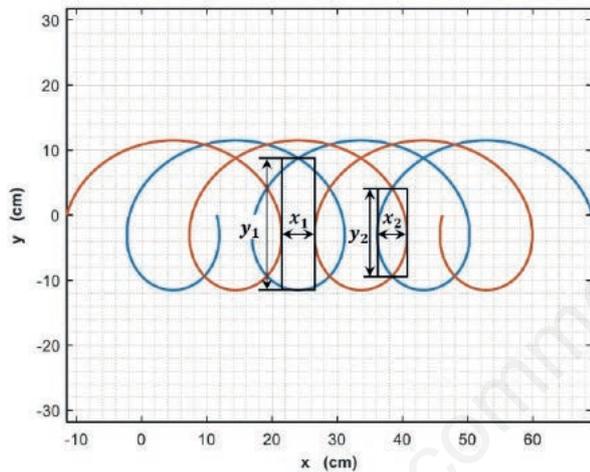


Figure 2. Size of the primary (x_1, y_1) and secondary (x_2, y_2) clods: nomenclature and graphic interpretation of the analysed clod.

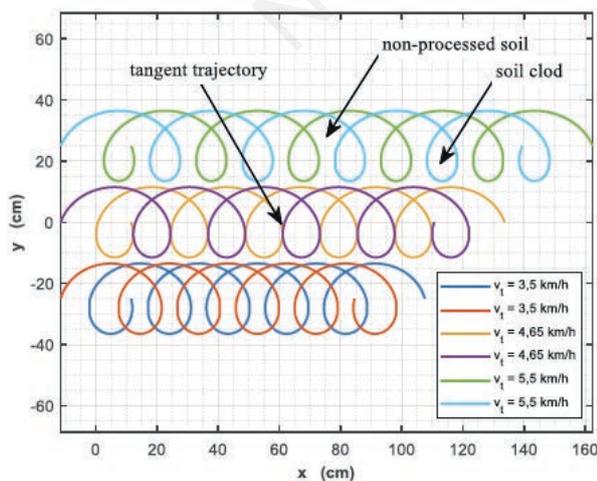


Figure 3. Rotor trajectories with two opposing tines $r = 0.120$ m and $\omega = 304$ rpm: effect of the change of the tractor speed v_t .

Analysis of the trajectories and of the clod sizes

The results obtained with three different average speeds v_m due to three different PTO rotation speeds (540, 750 and 1000 rpm) and the corresponding limit speeds (4.65, 6.45 and 8.65 km/h) are reported below. Figure 4A-C show the trend of the parameters x_1 ,

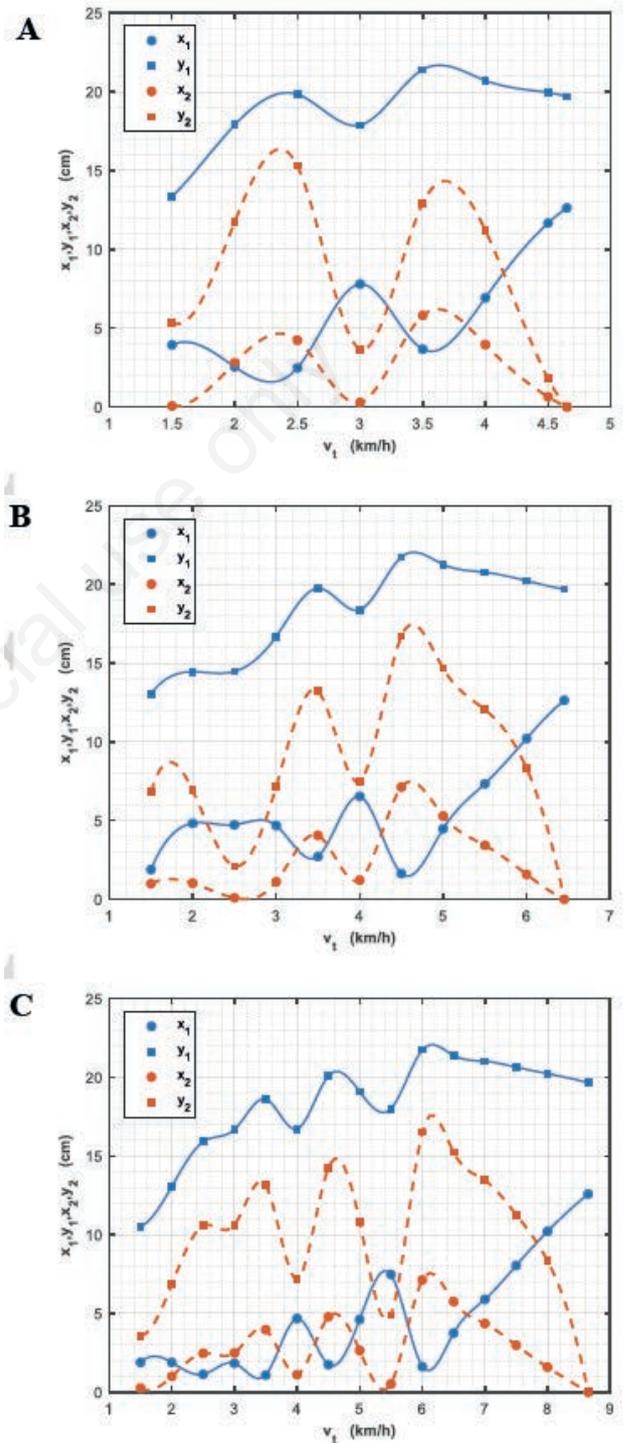


Figure 4. A) Sizes of primary (solid lines) and secondary (dashed lines) clods with $v_m = 14.1$ km/h and $r = 0.120$ m. B) Sizes of primary (solid lines) and secondary (dashed lines) clods with $v_m = 19.6$ km/h and $r = 0.120$ m. C) Sizes of primary (solid lines) and secondary (dashed lines) clods with $v_m = 26.2$ km/h and $r = 0.120$ m.

y_1, x_2, y_2 obtained from the analyses. The parameters x_1, x_2 show a trend characterised by points of maximum and minimum as the tractor speed v_t changes, also showing the possibility of obtaining similar clod sizes by choosing appropriate tractor speeds v_t . The parameters x_2, y_2 converge to zero near the limit speed, resulting in line with the definition of secondary clod adopted. The analysis carried out shows that the size of the clods does not always decrease for a decreasing speed v_t . On the contrary, it shows how, in particular conditions, these clod sizes increase at the expense of the quality of the soil processing. The tractor speed must therefore be set in relation to the angular speed of the rotors and the desired size of the clods.

A new parameter has been introduced, *i.e.* the area A of the rectangle in which the surface of the soil clod is inscribed. The area A is therefore the product of the individual dimensions of the clods and, respectively for the primary and secondary clods. Figure 5A shows, as an example, the trends of these quantities according to v_t . We can note how these trends are similar to those of x and y .

Another parameter considered is the total area worked in the unit of time A_{TOT}/t , where A_{TOT} is equal to the product of the actual width of the processing by the advancement of the tractor. Figure 5B and C show the trend of the areas A_1 and A_2 according to A_{TOT}/t . The graphs show that it is possible to process a comparable area of land using lower average speeds v_m for the benefit of the power required to the PTO (*i.e.* lower fuel consumption), leaving the final quality of the work unchanged. For example, a dimension of the clods around 34 cm^2 can be obtained considering $v_t = 4.5 \text{ km/h}$ (or equivalently $A_{TOT}/t = 3000 \text{ cm}^2/\text{s}$) with different average speed.

The sensitivity analysis of the rotor radius has been conducted in order to evaluate its influence on the clod size. Three different rotor radii (0.065 m, 0.085 m, 0.165 m) have been analysed in addition to the reference rotary harrow ($r = 0.120 \text{ m}$). It has been found that the ratio of the primary clods dimensions x_1, y_1 with respect to the equivalent dimensions of the reference harrow is constant and it is equal to the ratio of the rotors radius. The same result has been found for the secondary clod size.

Figure 6A shows the simulated trajectories of a harrow made up of four rotors that are counter-rotating and arranged along a straight line orthogonal to the tractor's travel direction, a typical solution currently in use. Each rotor is equipped with two cutting elements mounted opposite to each other. The number of rotors has been limited to four because a greater number would not have introduced further information useful for the analysis, since the trajectories are repeated equal to each other.

Figure 6A shows a problem with the final result of soil processing. In particular, there are areas of the processed surface, circled in black, that have a high density of trajectories (strong overlap) located on the same portion of the area. This is equivalent to obtaining an excessively fine localised soil structure with possible erosion phenomena. Other areas, on the other hand, have areas with a low density of trajectories (weak overlap), therefore the whole process produces as a final result an inhomogeneous soil structure.

Alternative rotary harrow construction solutions

The trajectories of an alternative rotary harrow, in the case in which all the rotors have the same direction of rotation, are shown in Figure 6B. The trajectories show significantly reduced areas with high density of tine passes in the same area. For this config-

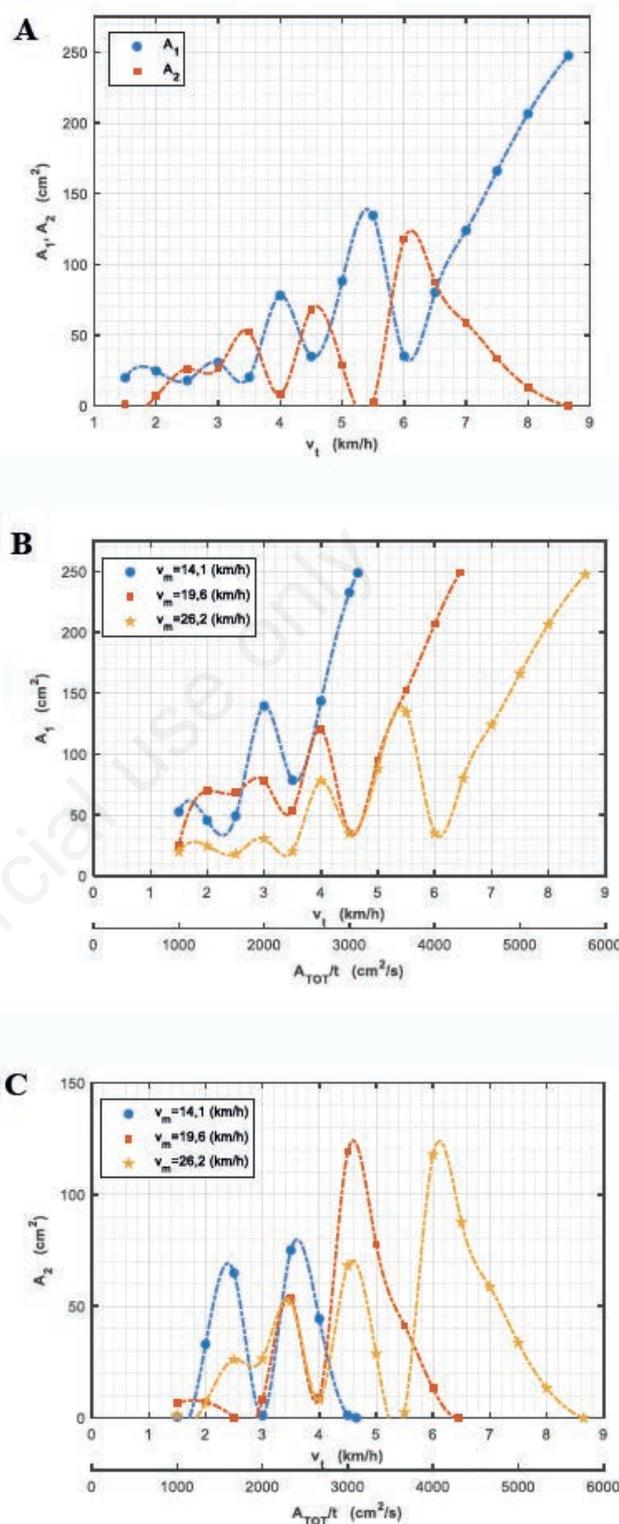


Figure 5. A) Sizes of primary A_1 and secondary A_2 clods with $v_m = 26.2 \text{ km/h}$ and $r = 0.120 \text{ m}$. B) Area A_1 depending on the total area per unit of time A_{TOT}/t evaluated at different average speeds v_m and $r = 0.120 \text{ m}$. C) Area A_2 depending on the total area per unit of time A_{TOT}/t evaluated at different average speeds v_m and $r = 0.120 \text{ m}$.

uration, the trend of the size of the clods remains similar to that obtained with the configuration of a counter-rotating rotary harrow. Further harrow construction solutions have been analysed; these are characterised by a different arrangement of the 'W' type rotors. The rotor centres are positioned between them according to the dimensions i_x and i_y , see Figure 7A. Figure 7B shows the trajectories of the knives obtained with an optimised configuration of a rotary harrow. The proposed solution reduces the problem of overlap illustrated above. In fact, observing the tracks of the knives one can observe clods of worked soil of homogeneous size over the whole working width of the harrow. On the other hand, coarser dimensions are found at the external rotors. This solution could be adopted to carry out soil tillage and seedbed preparation with a single tractor passage over the soil, thus avoiding soil compaction phenomena.

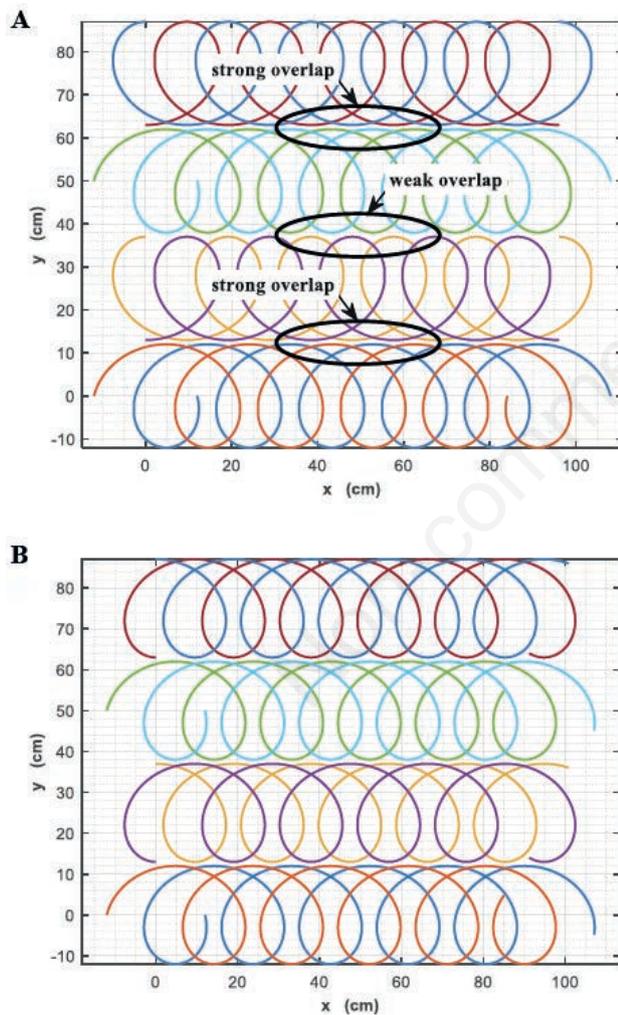


Figure 6. A) $r = 0.120$ m, $v_t = 3.5$ km/h, $\omega = 304$ rpm, four counter-rotating rotors, circled areas represents the areas with strong/weak overlap. B) $r = 0.120$ m, $v_t = 3.5$ km/h, $\omega = 304$ rpm, four rotors all rotating in the same direction.

Conclusions

In this study, a numerical model has been created that makes it possible to analyse the trajectories described in the soil by the tines of rotary harrows. The trajectories of the tines have been analysed according to the geometrical parameters of the harrow as well as the operating parameters, such as the tractor speed and the angular speed of the PTO. Furthermore, the primary clods and secondary clods formed during the working of the soil and their relative sizes have been defined.

The analysis carried out has highlighted the possibility of selecting appropriate combinations of tractor speed and angular speed of the rotors in order to optimise the final quality of the work and the amount of used power. Furthermore, innovative geometric solutions have been proposed regarding the arrangement of the

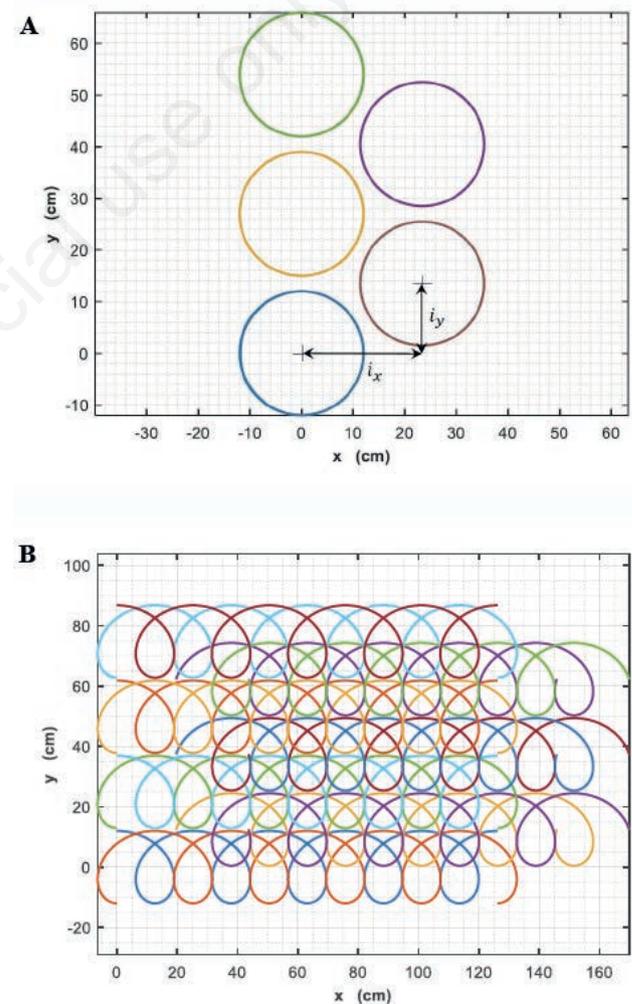


Figure 7. A) Generic geometric arrangement of the 'W' rotors. B) Trajectories due to an optimal arrangement of the rotors.

rotors, in order to obtain an optimisation of the size of the clods and their distribution on the surface treated by the harrow.

This study may form the basis for future developments involving the interaction between the harrow tines and the soil.

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