KINEMATICS OF THE ROTARY SUBSOILER AND PLOW – GYROTILLER

CINEMÁTICA DO SUBSOLADOR ROTATIVO E ARADO – GYROTILLER

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ABSTRACT
The first objective was to make a historic rescue of an equipment with an interesting principle, developed in 1925 - gyrotiller, a mix of subsoiler and rotary plow. It was widely used in the first decades of the last century, falling into disuse after the second world war. Historical notes with records of their performance are detected, especially from the 1920s and 1930s and on old-fashioned agricultural equipment websites, which still exist today. The second objective was to study the movements of the shanks: Using differential calculus as a tool, the equations of motion of the shanks of the aforementioned equipment are formulated, in order to predict some parameters of their behavior and develop a method for projects that might make use of its interesting soil tillage system. The equations are applied to three levels of linear tractor velocity, allowing us to predict the shank path and enable comparison to the fixed shanks of conventional subsoilers.

Keywords: Implement. Soil Tillage. Historical Note. Mathematical Approach. Differential Equations.

RESUMO
O primeiro objetivo foi fazer um resgate histórico de um equipamento com um princípio interessante, desenvolvido em 1925 - o girocultivador, uma mistura de subsolador e arado rotativo. Foi amplamente utilizado nas primeiras décadas do século passado, caindo em desuso após a segunda guerra mundial. Notas históricas com registros de seu desempenho são detectadas, especialmente das décadas de 1920 e 1930 e em sites antigos de equipamentos agrícolas, que existem até hoje. O segundo objetivo foi estudar os movimentos das hastes: utilizando o cálculo diferencial como ferramenta, as equações de movimento das hastes dos equipamentos mencionados são formuladas, a fim de prever alguns parâmetros de seu comportamento e desenvolver um método para projetos que possam fazer uso de seu interessante sistema de preparo do solo. As equações são aplicadas a três níveis de velocidade linear do trator, permitindo prever a trajetória da haste e possibilitar a comparação com as hastes fixas de subsoladores convencionais.

Palavras-chave: Implemento. Preparo do Solo. Nota Histórica. Abordagem Matemática. Equações Diferenciais.

RESUMEN
El primer objetivo fue rescatar la historia de un equipo con un principio interesante, desarrollado en 1925: el cultivador giratorio, una combinación de subsolador y arado

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rotatorio. Fue ampliamente utilizado en las primeras décadas del siglo pasado, cayendo en desuso tras la Segunda Guerra Mundial. Se han encontrado registros históricos de su funcionamiento, especialmente de las décadas de 1920 y 1930, así como en sitios web de equipos agrícolas antiguos, que aún existen. El segundo objetivo fue estudiar el movimiento de los vástagos: utilizando el cálculo diferencial como herramienta, se formulan las ecuaciones de movimiento de los vástagos del equipo mencionado para predecir algunos parámetros de su comportamiento y desarrollar un método para proyectos que puedan aprovechar su interesante sistema de labranza. Las ecuaciones se aplican a tres niveles de velocidad lineal del tractor, lo que permite predecir la trayectoria de los vástagos y compararla con los vástagos fijos de los subsoladores convencionales.

Palabras clave: Implemento. Labranza del Suelo. Nota Histórica. Enfoque Matemático. Ecuaciones Diferenciales.

1 INTRODUCTION

1.1 HISTORICAL NOTES

The Gyrotiller was not invented by Fowler, but by Norman Storey in Puerto Rico, for a sugar cane plantation. Charles Henry Fowler bought the patented design in 1925 and began producing the device. They were hugely expensive. Instead of buying it, there was a rental alternative offered by the company at a rate per acre. The First Machine left the factory to the Caribbean in October 1927. In order to operate, 150 hp - 170 hp crawler tractors were used (Fandom, 2017). In the present times, high power tire tractors for agricultural use have been developed. What would be the power of tire tractors nowadays? Applying the equation (Stolf, 2016): PRt (tire) R= 1.42 ● PRc (crawler)R +29.9, for 150 - 170 hp, results 243-270 hp respectively. This is an estimate of the power range of modern tire tractors for operating a gyrotiller.

During World War II, gyrotillers were used by contractors in the United Kingdom to bring many thousands of acres of previously uncultivated land into production (Flick, 2019). According to Cookham (2008), before World War II Belgium had for centuries carried out the cultivating of arable land in the Thames Valley using strong breed horses as traction power. Farmers began to realize that their arable land was not draining, due to potential "clay hardpan". Single-shank cultivators would break up. However, the low operating capacity of animal traction became a problem. The solution came with the gyrotiller. This very expensive machine could be hired from an Agricultural Contractor. The machine became so popular among farmers that it was working twenty-four hours a day with its own floodlight system. It could break up hardpan down to 18-20 inches (46 - 51 cm). In this website, there is a good view of a gyrotiller.

An unknown cist (antique coffin) was accidentally hit by a gyrotiller in a tillage operation in Berwickshire (Kennedy and Scot, 1939). This note reveals that the working depth was 14 inches (36 cm).

1.2 SCIENTIFIC PUBLICATIONS (2)

In terms of scientific papers, Culpin (1936) published an extensive study on the effect of gyrotillers on soil. A general account is given of four experiments in which the action of the Fowler Gyrotiller on soil was compared with traditional cultivation implements. In a poor gravel soil with a marked tendency to form a hardpan just below the normal cultivation depth, the gyrotiller succeeded in breaking up this pan and worked the soil to a depth of 12-16 inches

(31 - 41 cm). The gyrotiller has produced well- marked changes in the soil on both heavy and light land. The resistance measurements are, statistically, demonstrably lower on the gyrotilled plots than on the controls for a considerable time after this tilling, and a method of soil fixation has shown that small cavities persisted for more than a year. In one experiment, significant statistical differences ($p < 0.05$) in resistance have been shown to exist up to 19 months after gyrotilling.

In two long-term experiments on heavy land, the gyrotiller has been compared with normal cultivations (plowing and subsoiling, or plowing alone) by Garner and Sanders (1938). No significant increase in yield has been obtained, although in five out of seven experimental crops the difference was very slightly in favor of gyrotilling.

1.3 MACHINE VISION (VIDEOS AND PICTURES)

The best visualization found refers to a video by Henderson and O'Hara (2016) and another by George (1939).. They give a good idea of how the gyrotiller works the land. Another video shows a large gyrotiller moving across a field at night (Ward, 1938), while Cookham (2008) and Flick (2019) show representative photos of the equipment.

1.4 GYROTILLER: PLOUGH OR SUBSOILER

A subsoiler or flat lifter is a farm implement used for deep tillage, loosening and breaking up soil at depths below the levels worked by disc or moldboard ploughs.

Although called “gyrotiller plow”, the concerned implement has two traits that allow it to be classified as a subsoiler: 1) its action bodies are shanks/rods and not discs or moldboards, and 2) it has a comparatively greater working depth. According to data already mentioned, its working depth is on average 40 cm: 36 cm (Culpin, 1936), 36 cm (Kennedy and Scot 1939), and 49 cm (Cookham 2008)], and it is used to break hard-pan. Therefore, in this study, the implement is analyzed as being a subsoiler.

As noted, the device aroused great interest in Agriculture, especially in the 1920s and 1930s. Then there was a gap until today. It survives through old-fashioned equipment websites and two old records of scientific paper.

This work has the aim developing mathematical equations to describe the motion of gyrotiller shanks, simulating some working conditions, translating their movement into graphs, and comparing it with the motion of conventional subsoiler shanks.

2 MATERIAL AND METHOD

2.1 DEVELOPMENT OF GYROTILLER SHANK MOVEMENT EQUATIONS

A description of its movement was found by searching the classic literature of applied mathematics and through a particular type of cycloid called elongated cycloid (Bronstein and Semediaev, 1968; Leithold, 1982; Piskounov, 1983):

2.1.1 Device Characteristics

It is a rear hitch implement, with differential movement transmitted by power take-off (PTO), the structure designed to withstand high efforts, coupled to crawler tractors in the power range of 150 hp - 170 hp.

Figure 1 shows a schematic representation. The active part consists of two horizontal circular platforms, \with counterclockwise rotation movement on the left and clockwise on the right, when viewed from the rear.

Six vertical subsoiling shanks are peripherally and symmetrically distributed underneath each platform.

The radius measured from the subsoiler shoe is 0.8 m, the implement's working width is 4 ● 0.8 = 3.2 m, and the operational rotation velocity is 30 rpm (0.5 rps).

2.1.2 Symbology

x: tractor displacement direction (m).

y: direction perpendicular to tractor
displacement (m). t: time (s).

v: tractor displacement velocity (constant) (m s^{-1}).

R: shank radius (constant) (m).

N: shank constant frequency (rotation velocity) (rps). 1/N: shank single-rotation time (s).

Vp: shank tangential peripheral velocity (constant) on platform
= 2πRN. V: shank resultant velocity (m s^{-1}) relative to the soil

Vx: shank velocity in the x direction (m s^{-1}) relative to the soi

Vy: shank velocity in the y direction (m s^{-1}) relative to the soil

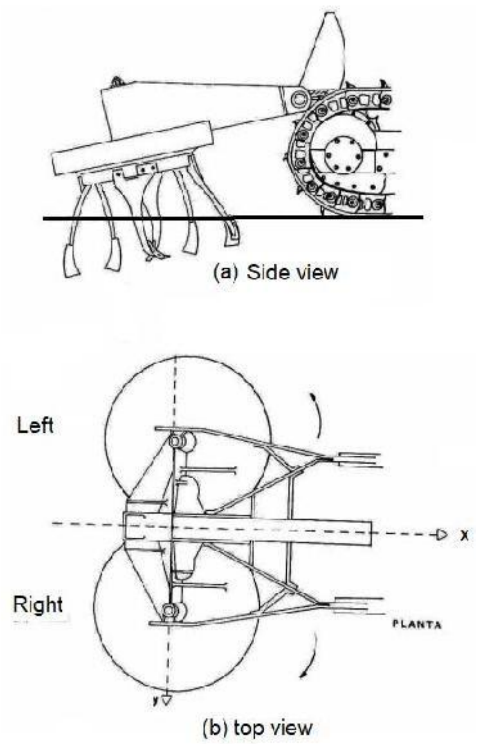
L: shank path (m).

u: angle made (rads) = 2πRN

E: efficiency of a rotary subsoiler shank in relation to conventional shanks for the same tractor itinerary: linear meters worked by a rotary shank divided by linear meters worked by a fixed shank.

Figure 1

Gyrotiller (a) schematic representation of right platform with 6 shanks; (b) top view of both platform



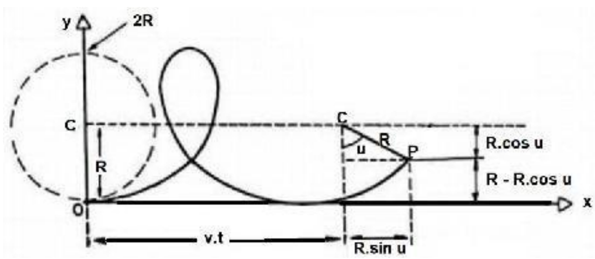
2.1.3 Equation Deduction

If equations are developed for one shank, the others will derive from them.

In Figure 2, a left platform shank with counterclockwise rotation positioned at zero is considered, where R is the radius and C is the platform center.

Figure 2

Motion of a left platform shank. Point P: position of the shank after time t



From the beginning, after a time t, the shank makes an angle to the platform that depends on time itself and the angular velocity ($2\pi N$), which can be represented in radians according to the formula:

$$u = 2\pi Nt \qquad (1)$$

In addition to the rotation movement, the shank also moves because point C moves with the tractor at a constant velocity v in the x direction. Thus, after a time t, point C will have covered a distance vt.

Considering the combination of these two motions, a basic question arises: Where will the shank be after a given time t? - Defining its position through the x and y coordinates, the answer is:

in $x = vt + R\sin(2\pi Nt)$ ••• eq. 1 in $y = R$
$- R\cos(2\pi Nt)$ ••• eq. 2 (2)

When v, R and N are known and t values are given, x and y pairs are generated, allowing the graph of the shank movement to be drawn.

Unlike conventional subsoilers, the shank does not move at tractor velocity. Deriving equations 1 and 2 in relation to time, velocity components are obtained for both directions of rotation:

in x: $V_x = dx/dt = v + 2\pi RN\cos(2\pi Nt)$ (3)

in y: $V_y = dy/dt = 2\pi RN\sin(2\pi Nt)$ (4)

But $2\pi RN$ is the peripheral velocity (V_p) of the shank on the platform in m s-1.

Therefore

Vx = dx/dt= v + Vp cos(2πNt) (5)

Vy = dy/dt = Vp sin(2πNt) (6)

And the resultant velocity is:

$$V = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} = \sqrt{(Vx)^2 + (Vy)^2}$$ (7)

Using equations 3 and 4 in this expression, and remembering the property $(\sin u)^2 + (\cos u)^2 = 1$, then:

$$V = \sqrt{v^2 + (Vp)^2 + 2v.Vp.\cos(2\pi Nt)}$$ (8)

This expression shows the different subsoiler velocities per cycle relative to the soil.

Another interesting aspect to be analyzed is how much the rotary subsoiler works more than the conventional ones, i.e., what is the length of its trajectory, L?

dL = Vdt (9)

Therefore

$$L = \int_0^t V dt$$ (10)

Substituting the value of V in equation 11, we have:

$$L = \int_0^t \sqrt{v^2 + (Vp)^2 + 2v.Vp.\cos(2\pi Nt)}\, dt \ldots\ldots\ldots$$ (11)

This integral is not exact. The most important is to find L for a time interval in which the shank makes a complete rotation, i.e., t=1/N. STOLF (1987) studied an approximate solution where the error depends on the v/Vp ratio, but never exceeds 11%, resulting in:

$$L\ of\ the\ cycle = \int_0^{t=1/N} \sqrt{v^2 + (Vp)^2 + 2v.Vp.\cos(2\pi Nt)}\,dt = (\sqrt{v^2 + (Vp)^2})/N \qquad (12)$$

Equation 7 allows us to determine the distance subsoiled by a shank when the platform performs one revolution.

Since the revolution time is 1/N, in this interval the tractor travels a distance L = v/N, the same as a

fixed shank, if the tractor was operating a regular subsoiler. Therefore, the relative work efficiency (rotary/common) can be established by dividing equation 7 by this last expression, resulting in:

$$E = \sqrt{(v^2 + (Vp)^2)/v^2} = \sqrt{(1 + (Vp/v)^2} \qquad (13)$$

In other words, it translates how many times the rotary shank travels relative to the tractor that operates it.

2.1.4 Situations to be Simulated

Using the drive system of a crawler tractor engine, the implement has a constant rotation velocity of 30 rpm (0.5 rps), however, tractor velocity can vary through the gears without changing rotation velocity. If N = 0.5 rps and R = 0.8 m, then shank peripheral velocity is: Vp = 2πRN = 2.51 m s^{-1} (9.04 km h^{-1}).

With these constant parameters, three working conditions were simulated, generated by different tractor velocities:

$v1 = 2$ km $h^{-1} = 0.56$ m s^{-1}.

$v2 = 4$ km $h^{-1} = 1.11$ m s^{-1}.

$v3 = 10$ km $h^{-1} = 2.78$ m s^{-1}.

The unit m s-1 is used for velocity in calculations, and results are also presented in km h-1 to facilitate the perception of order of magnitude.

3 RESULTS AND DISCUSSION

The three proposed situations are analyzed below: Velocity v1 (2 km h-1) within implement range).

Velocity v2 (4 km h^{-1}) within the operating range of conventional subsoilers).

Velocity v3 (10 km h^{-1}) is of theoretical interest, when tractor velocity becomes greater than peripheral shank velocity Vp = 9 m s-1, at 30 rpm and a radius of 0.8 m (v3>Vp, i.e, elongated cycloid)

The equations will be applied to the first case. However, for the other cases, only results will be presented, as they derive from the first one.

3.1 SHANK WORKING VELOCITY AND EFFICIENCY FOR v1 = 2 km h^{-1} = 0.56 m s^{-1}

The velocity at which the shank works the soil is (eq. 13):

$$V = \sqrt{0{,}56^2 + 2 * 0{,}56 * 2{,}51\cos(\pi t)} \qquad (13)$$

Vmax and Vmin occur when cosine is 1 and -1, and are respectively:

Vmax= 3.07 m s^{-1} (11.1 km h^{-1})

Vmin = 1.95 m s^{-1} (7.0 km h^{-1})

Efficiency (equation 14) is:

$$E_1 = \sqrt{1 + (2{,}51/0{,}56)^2} = 4.59 \qquad (14)$$

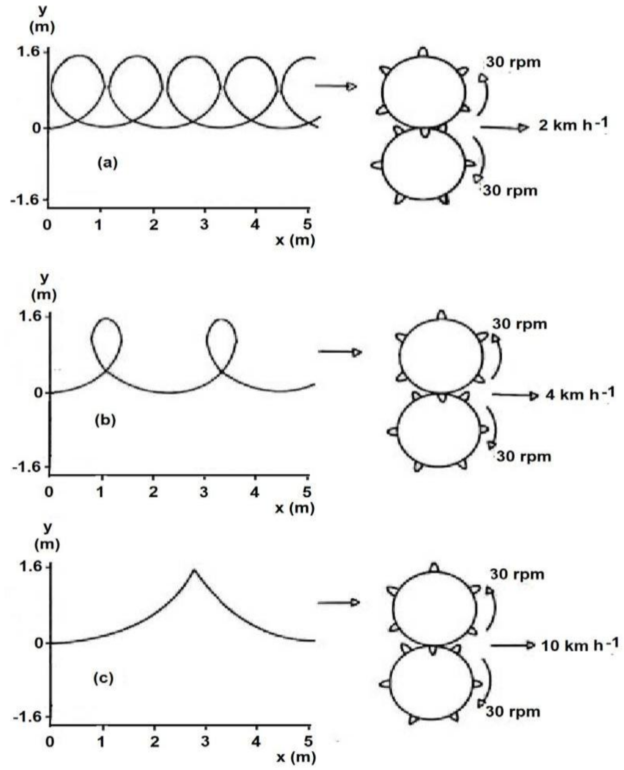
This means, for example, that while the tractor covers 100 m, the shank subsoils 459 linear meters, whereas a fixed shank subsoiler would obviously subsoil only 100 m.

As the Gyrotiller is made up of 12 shanks, it "is equivalent" to a conventional 55-shank subsoiler (12•4.59). Its working width is 3.20 m, therefore, it mobilizes the soil as if it were a conventional subsoiler with a distance of 0.06 m (3.2/55) between shanks, or 4 (4.59) subsoilers with a distance of 0.6 m between shanks.

The same procedure was applied to the other cases, and data is shown in table 1.

Figure 3

Left shank path for the three tractor velocities: (a) 2 km h-1; (b) 4 km h-1; (c) 10 km h-1



Angular velocity = 30 rpm, peripheral velocity = 9 km h-1

Table 1

Comparative parameters resulting from three tractor velocities, with constant peripheral velocity of shank on platform: (Vp = 9 · km h-1)

Tractor Velocity	Shank Soil Working Velocity	Shank Working Efficiency
v1=2 km h^{-1}	Vmin1=7 km h^{-1} Vmax1=11 km h^{-1}	E1=4.59
v2=4 km h^{-1}	Vmin2=13 km h^{-1} Vmax2=5 km h^{-1}	E2=2.37
v3=10 km h^{-1}	Vmin3=19 km h^{-1} Vmax3=1 km h^{-1}	E3=1.35

3.2 GRAPHIC SHANK PATH FOR v1 = 2 km h^{-1}= 0.56 m s^{-1}

Assuming v1 = 0.56 m s-1, R = 0.8 m and N = 0.5 rps, the position coordinates (equations 1 and 2) for v1 have to be found: x1 = 0.56 t + 0.8 sin (πt) y1 = 0.8 - 0.8 cos (πt)

By assigning time values using 0.1 s intervals, pairs of values (x, y) were obtained, and the data plotted in a graph representing the shank path in the soil (Figure 3a). Using the same procedure for v2 and v3, the respective paths were found (Figures 3b and 3c).

Figure 4 represents the paths of the 12 shanks for each case, obtained by considering the proper angle offset, i.e., Δu=2π/6 between shanks.

There is a natural concern that the implement might cause soil compaction. However, the shanks do not work in a single direction, they occupy different positions. It is interesting to remember that moldboard or disc plows do continuous in-depth contact work through the interposition of shares (discs), which are more likely to create pans.

4 CONCLUSIONS

a) The application of this method made it possible to develop equations for the device's motion parameters, allowing a complete analysis of this type of project, including a graphic path of the implement under normal working conditions (2 km h-1 and 30 rpm), at a velocity v1 (2 km h-1); at the velocity of conventional subsoilers (4 km h-1, 30 rpm) and at a velocity higher than the peripheral velocity of the shanks (10 km h-1, 30 rpm).

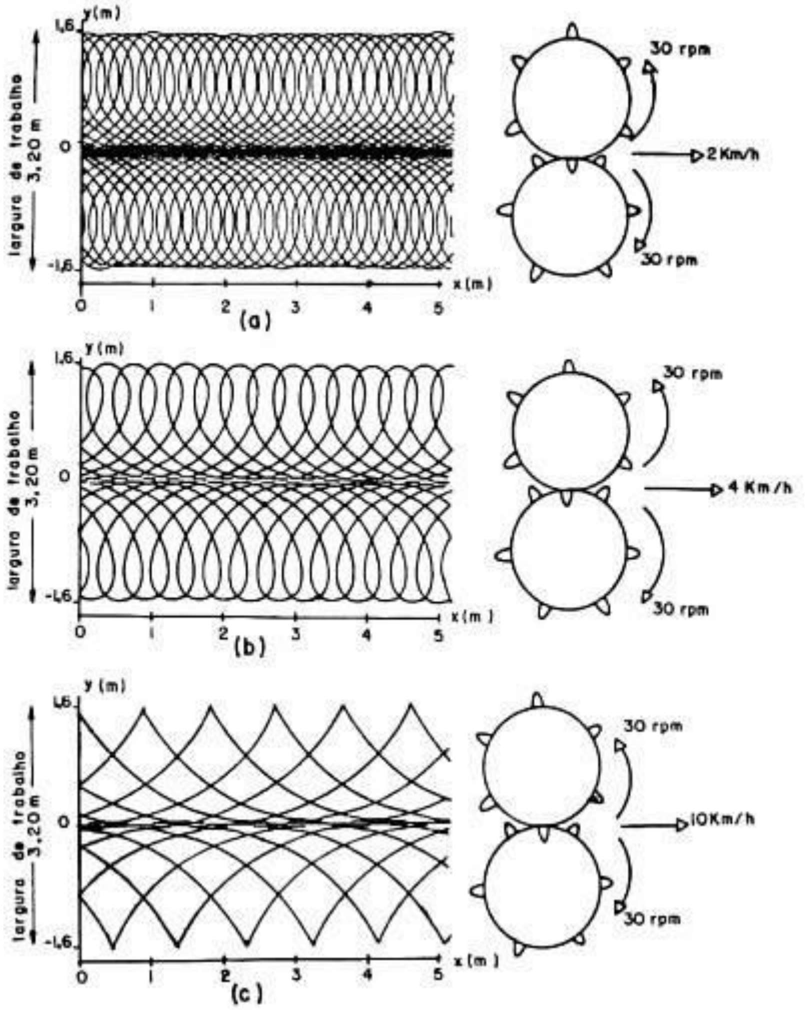
b) Under normal conditions, a Gyrotiller shank describes a path 4.6 times greater than the fixed shank of a conventional subsoiler (E = 4.6). The 12 shanks in operation are equivalent to a 55-shank subsoiler operating in a 3.20 m-wide strip, i.e., as if it were a conventional subsoiler with a distance of 6 cm between shanks.

c) It is an excellent project from a kinematic point of view, working the soil in a relatively homogeneous way (Figure 4a). When necessary, if any parameter needs to be changed, it should be to increase virtual distance by decreasing rotation velocity, increasing tractor velocity, and/or decreasing the number of shanks.

d) As a general conclusion, this method provides equations to determine the device's motion parameters, where the no. of shanks, platform radius, angular velocity, and linear set velocity can be modified. That is, it allows the development of projects for versions that are different from the original equipment.

Figure 4

Path of the 12 subsoiler shanks for three tractor velocities



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