ENERGETICS OF PULLING FLAX STALKS WITH A DISC-BELT FLAX-PULLING APPARATUS
/
ЕНЕРГЕТИКА БРАННЯ СТЕБЕЛ ЛЬОНУ ДИСКОВО-ПАСОВИМ ЛЬОНОБРАЛЬНИМ АПАРАТОМ

Svitlana YUKHYMCHUK, Serhii YUKHYMCHUK*), Mykola TOLSTUSHKO, Igor TSIZ, Nataliya TOLSTUSHKO

Lutsk National Technical University, 75, Lvivska str., Lutsk, Ukraine;
*) *Tel: +380956447720; E-mail:* sergei-71@*ukr.net*
DOI: https://doi.org/10.35633/inmateh-71-32

Keywords: *pulling, flax stalks, disk-belt pulling apparatus, pulling stream, power, energy*

ABSTRACT
The article describes a new design of the disc-belt flax-pulling apparatus, which will increase the durability of the pulling belts and reduce the material consumption of the flax gleaning machine. The geometrical parameters of the pulling section of the disc-belt flax-pulling apparatus have been established. The energetics of the process of picking flax stalks, which are clamped in the curved longitudinal pulling stream of the disc-belt flax-pulling apparatus, have been theoretically investigated. The dynamics of changes in the components of pulling power when moving the flax stalk along the pulling stream were studied, depending on: the initial inclination of the flax stalk; from the forward speed of the flax harvester; from the angle of inclination of the pulling apparatus to the horizon. The energy per second of pulling and the value of its components are determined.

РЕЗЮМЕ
У статті дано опис нової конструкції дисково-пасового льонобрального апарата, яка дозволить підвищити довговічності бральних пасів та зменшити матеріаломісткість льонозбиральної машини. Встановлено геометричні параметри бральної секції дисково-пасового льонобрального апарата. Теоретично досліджено енергетику процесу брання стебел льону, які затискаються у криволінійному поздовжньому бральному рівчаку дисково-пасового льонобрального апарата. Вивчено динаміку зміни складових потужності брання при переміщенні стебла льону по бральному рівчаку в залежності: від початкового нахилу стебла льону; від поступальної швидкості льонозбиральної машини; від кута нахилу брального апарата до горизонту. Визначено секундну роботу брання та значення її складових.

INTRODUCTION
At all times in the centuries-old history of mankind, fibre flax has been grown by people to obtain fibre and seeds (*Karg, Sabine, 2022*). It also provides a third valuable product – shives. The distinctive feature of fibre flax is that the entire plant is used for human health (*Jhala and Hall, 2010*).

In the rapidly deteriorating environmental situation in the world, the population has realized the great importance of flax for health, the need to use environmentally friendly and healthy food, clothing, and a favourable living environment. Linen fabrics, linseed oil, and other products containing flax fibres are of great benefit to human health (*Omer et al., 2020*).

No other fibres can yet surpass the remarkable natural properties of flax, which creates comfortable conditions for the person wearing them. Developed methods for modifying flax fibre make it possible to use all the fibre contained in the stem, as well as waste from shaking and combing, to produce thin, cheaper household fabrics mixed with other fibres *(Yang et al., 2009*).

Even low-grade flax fibre is successfully used by foreign companies for reinforcing composites in the production of automobiles, as well as in aircraft, ship and carriage construction for sound, vibration and thermal insulation of passenger compartments, etc. (*Dudarev and Say, 2020*).

From flaxseeds, flaxseed oil is obtained for technical purposes and dietary medicinal food, which contains omega-3 fatty acids (*Zuk et al., 2015*). The latter provides a significant medicinal effect for various human diseases. Also, seeds are a source of protein, soluble polysaccharides, phenolic acids and flavonoids and other biologically active components.

The addition of flaxseeds and oil in the manufacture of bakery and confectionery products has a preventive effect on the human body (*Charney, 2014*).

Eco-friendly structural and thermal insulation materials are made from flax shives (*Yaghelyuk et al., 2020*). Structures with wall elements made from such materials have low heat loss and can be used in residential construction (*Jhala and Hall, 2010*).

Currently, Ukraine is dependent on cotton-growing countries for raw materials. Therefore, to ensure the economic and strategic independence of the country, it is extremely important to have domestic cellulosic fibrous raw materials to produce, for example, cotton wool, fabrics for the army, non-woven materials and threads for medicine, gunpowder and explosives from flax nitrocellulose (*Dudarev and Khomych, 2022*).

The quality and yield of flax varies greatly depending on weather conditions, soil type, varieties, cultivation techniques and other factors (*Lafond et al., 2008; Pisupati et al., 2021*). Fibre flax stems have a diameter of about 1.4–1.6 mm and a total height of up to 1.1–1.2 m (*Nag et al., 2015*) and one of the highest slenderness factor (i.e. the ratio between height and diameter of the stem) among botanical herbs and trees, which is about 365±33 (*Goudenhooft et al., 2019*). In the world, the yield of fibre flax straw is varied widely from 220 kg/ha to 4370 kg/ha depending on the country and weather conditions of cultivation (*Zając et al., 2012*). The seed yield is ranged from 270 kg/ha to 890 kg/ha/ (*Hall et al., 2016*). The seeds of the fibre flax contain 20–40% oil (*Zuk et al., 2015*).

For fibre flax, a seeding rate of 1800 seeds/m^2 is the better compromise long fibre yield, fibre mechanical performances and stem stability to lodging (*Bourmaud et al., 2016*).

The complex of flax harvesting operations begins with pulling the stalks out of the soil by the energying bodies of flax harvesters (*Abdel-Wahab et al., 2012*). Flax is harvested by pulling because the entire stalk is pulled from the soil and the productive part of the stalk, which contains fibre, is not lost with the stubble, which occurs during mowing (cutting) of flax (*Mańkowski et al., 2018*). When the streams of stalks are combined at the exit from the harvesters, a ribbon of flax stalks is formed (*Soucek et al., 2017*). All subsequent technological operations carried out on flax stalks in the field and during primary processing up to the separation of the fibre are carried out on the stalks in the ribbon. That is why, pulling flax and forming a ribbon is a technological operation where the parameters of the flax ribbon create the conditions for the efficient course of all subsequent technological operations (*Dudarev, 2020*).

Pulling apparatuses are used to pull flax stalks out of the ground during the mechanized harvesting of flax. Most often, these are belt and belt-disc pulling apparatuses (*Dudarev, 2015).*

In belt pulling apparatuses, the stalks are clamped between two pulling belts, which energy as belt transmissions, in which the working branch is tensioned. The belt covers the drive and driven pulleys, or the drive pulley and tension rollers.

In belt-disc pulling apparatuses, flax stalks are clamped between the pulling belt and the pulling disc. At the same time, the pulling disk rotates from contact with the pulling belt. That is, the belt is even more loaded than in the belt pulling apparatus.

Pulling belts are made of rubber reinforced with kapron threads and in the process of energy are stretched and need to be periodically tightened, and when worn, they need to be replaced.

In addition, these designs of pulling apparatuses are quite material-intensive. This is due to the use of pulleys, tension and support rollers, complex drive *(Dudarev et al., 2014).*

Therefore, it is urgent to develop such a design of the pulling apparatuses that would eliminate the mentioned shortcomings.

MATERIALS AND METHODS

We offer a new design of the disc-belt pulling apparatus (*Yukhymchuk et al., 2022*). In it, the drive is carried out directly on the pulling discs, and the passes press the flax stalks to the surface of the pulling discs. That is, the belt does not transmit torque from the driving to the driven pulleys, which means that it stretches less during operation. The pulling apparatus is tilted at an angle to the horizon.

Fig. 1 schematically shows the proposed disc-belt flax pulling apparatus.

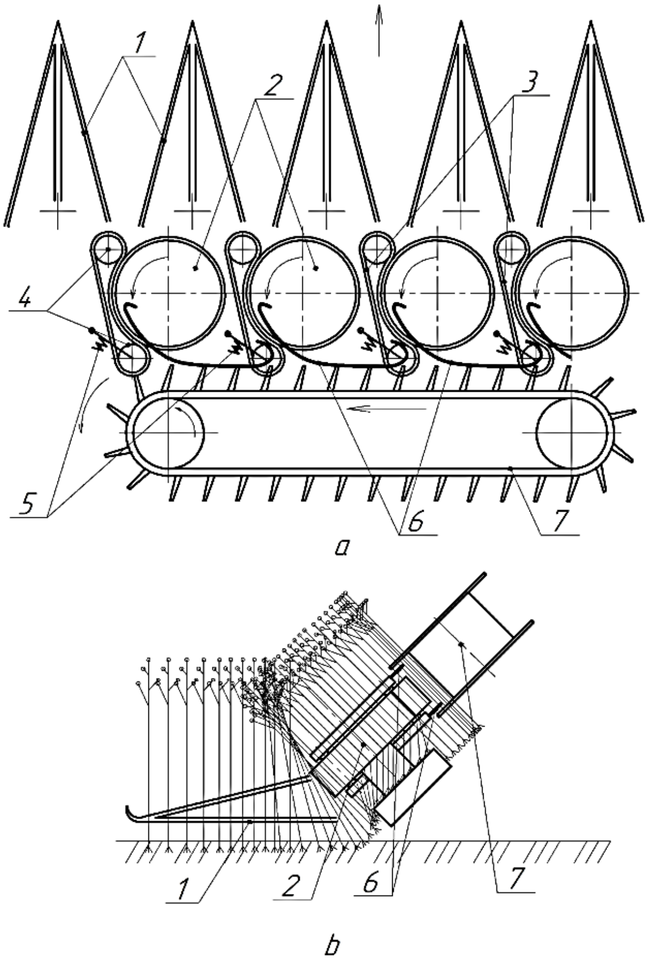

Fig. 1 - Disc-belt flax pulling apparatus

a – top view, b – side view

1 - dividers, 2 - pulling discs, 3 - pulling belts, 4 - rollers, 5 - spring-loaded fasteners, 6 - guide bars, 7 - transverse conveyor

The disc-belt flax pulling apparatus includes: a prefabricated frame (not shown in the figure); dividers *1*, pulling unit, which includes pulling disks *2*, pulling belts *3*, rollers *4*, spring-loaded fasteners *5*, guide bars *6*, transverse conveyor *7*.

The disc-belt flax pulling apparatus works as follows.

The drive of the pulling discs, which rotate in the same direction, is carried out from the frame crankcase. On the one hand, each pulling disk *2* is covered by a pulling belt *3*, which is put on rollers *4*. Due to the spring-loaded fastening *5* of the upper roller *4*, constant tension of the pulling belt *3* is ensured, which means the pressure in the pulling shaft.

When the machine moves along the surface of the field, the dividers 1 divide the flax stalks into separate strips and direct them to the mouths of the pulling streams. Further, the flax stalks are clamped between the contacting surfaces of the pulling discs 2 and pulling belts 3, pulled out of the ground and moved to the exit from the pulling streams, where they are captured by the fingers of the transverse conveyor 7 and, sliding along the surface of the guide rods 6, are moved to the exit from the disc-belt flax pulling apparatus. Later, depending on the type of flax harvesting machine, the stalk tape is either spread on the flax field, or fed to the following working bodies of the flax harvesting machine for combing the seed pods.

The pulling assembly contains fewer parts, so the proposed disk-belt flax pulling apparatus is less material-intensive compared to analogue ones. Due to the fact that the pulling belts do not transmit traction forces, but only clamp and hold the flax stalks, as well as the presence of spring-loaded upper rollers 4, the durability of the pulling belts is ensured.

For further studies of the new disc-belt flax pulling apparatus, it is necessary to conduct an energy analysis of the pulling process. Namely, to determine the dynamics of changes in the components of pulling power when moving the flax stalk along the pulling stream under different working conditions.

The geometric dimensions of the pulling section will be selected with the help of a sketch layout, using the Kompas computer program. Analogously to the existing four-handled pulling apparatuses, the width of one pulling section *B*=380 mm is considered (*Yukhymchuk et al., 2022*).

When choosing parameters, two conditions were taken into account. The first: the length of clamping the stalks in the pulling stream should be as long as possible to ensure the pulling of stalks of different characteristics (height, slope) and at different speeds of the unit. The second condition: the branches of the pulling belt, which is driven from the pulling disk, must not touch each other.

As a result of the graphic layout, the following geometric parameters of the pulling section were obtained (fig. 2): the distance between the centres of the pulling discs was 380 mm; radius of the rubberized pulling disc *R*=160 mm; the diameters of the belt transmission rollers were 80 mm, the thickness of the pulling belt was 10 mm; the gap between the pressing and overlapping branches of the belt, provided that there are no stalks in the grab rail, was 15 mm; the length of the belt was 1000 mm; the width of the pulling disc and the pulling belt, by analogy with the existing designs of belt pulling apparatuses, was 100 mm. The contact zone of the pulling disk and the pulling belt *AB* corresponds to the angle of reach of the pulling disk $\alpha = 80^o$, which in terms of the length of the reach zone is: $L = 2\pi R \frac{\alpha}{360^o} = 2 \cdot 3.14 \cdot 160 \cdot \frac{80^o}{360^o} \approx 223$ mm. It is worth noting that when pulling flax, when there are flax stalks between the pulling disc and the pulling belt, this zone increases. So, if it is assumed that the stalks are pressed into one layer with a thickness of 1 mm, this zone will be characterized by an angle $\alpha = 86^o 30'$ and a length of $L \approx 241$ mm. And with a greater thickness of the stalk tape, the clamping zone will increase even more.

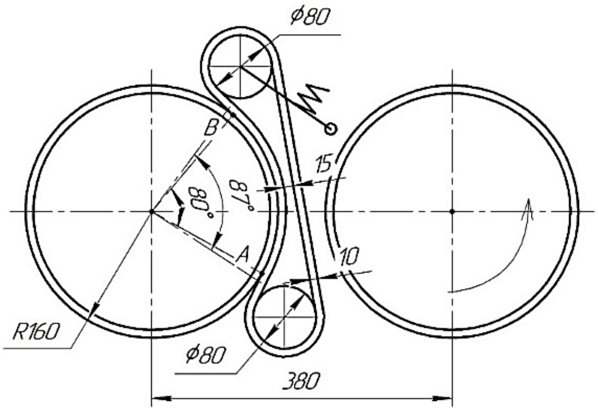

Fig. 2 - Structural diagram of the pulling section

The pulling apparatus performs two main functions - pulling flax stalks out of the ground and transporting them to the transverse conveyor. At the same time, the stalks clamped in the pulling streams carry out a complex movement, namely: relative movement under the action of the movement of the pulling belt and portable - during the movement of the machine.

Figure 3 shows a schematic representation of the frontal projection of the pulling apparatus in the Cartesian coordinate system *X′O′Y′*. The *O′Y′* axis is placed horizontally and directed to the right, and the *O′X′* axis is directed down.

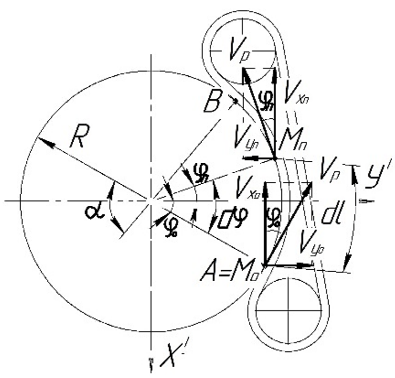

Fig. 3 - The scheme for determining the velocities of the stalk in the pulling stream

The flax stalk is conventionally marked by a material point M, which moves in the $X'OY'$ coordinate system along the curve AB. At the same time, the speed of the point M in the pulling stream Vp coincides with the circular speed of the pulling disk rim and the speed of the pulling belt movement (fig. 3). The velocity V_p forms a certain variable angle φ with the axis OY', depending on which the projection $V_{x'}$ acquires either positive or negative values. The projections of the velocity V_p on the axis OX' and OY' are equal:

$$\left.\begin{aligned} V_X &= V_p \cdot \cos\varphi; \\ V_Y &= V_p \cdot \sin\varphi. \end{aligned}\right\} \tag{1}$$

On the curvilinear sections of the pulling streams, the angle φ is equal to the acute angle between the radius of curvature drawn to the point M_n and the $O'X'$ axis (fig. 3), since the velocity V_p is directed tangentially to the curve and the vector V_p forms a right angle with the radius.

When moving along the pulling stream, the stalk of flax - point M_n will travel a distance dl in some time dt, which is equal to:

$$dl = V_p \cdot dt \tag{2}$$

This same path dl can be expressed in terms of the corresponding change in the angle $d\varphi$ as some length of the arc of a circle:

$$dl = R \cdot d\varphi \tag{3}$$

where R is the radius of the pulling disk.

Before that, the movement of the flax stalk was considered only under the influence of the rotation of the pulling disc, not taking into account the influence of the forward movement speed of the flax harvesting machine V_m. Under the influence of the last factor, the stalk also acquires a transfer speed V_m.

The process of harvesting flax stalks was considered in the $XYZO$ spatial coordinate system (fig. 4). The stationary coordinate axes OX, OY, OZ were placed in such a way that the OX axis is parallel to the speed of the machine movement V_m, the OY axis is parallel to the plane of the pulling apparatus and directed in the direction of movement of the clamped stalks, the OZ axis is perpendicular to the field surface and directed upwards. At the same time, the axis $O'X'$ of the frontal plane of the pulling apparatus forms an angle β with the OX axis - the angle of inclination of the pulling apparatus to the horizon, and the axis $O'Y'$ is parallel to the axis OY.

At the same time, the velocity V of the point M_n in the spatial coordinate system represents the vector sum of the projections V_x, V_y, V_z, where:

$$\left.\begin{aligned} V_x &= V_{px} + V_m = V_{x'} \cos\beta + V_m = V_p \cos\varphi \cos\beta + V_m, \\ V_z &= V_{pz} = V_{x'} \sin\beta = V_p \cos\varphi \sin\beta, \\ V_y &= V_{py} = V_{y'} = V_p \sin\varphi. \end{aligned}\right\} \tag{4}$$

With the known projections of the velocities V of the M_n point, find the projections on the OX, OY, OZ coordinate axis of the displacements dX, dY, dZ of the M_n point depending on the time dt:

$$\left.\begin{aligned} dX &= V_x dt, \\ dY &= V_y dt, \\ dZ &= V_z dt. \end{aligned}\right\} \tag{5}$$

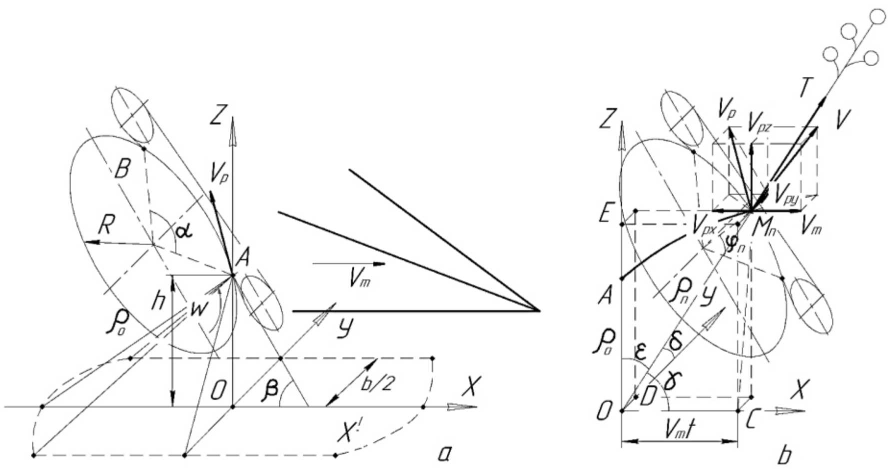

Fig. 4 - Calculation scheme of the stalk pulling process

Expressing the curved section *dt* in terms of $d\varphi$ and equating the right-hand sides of formulas (2) and (3), there is:

$$dt = \frac{R}{V_p} d\varphi \tag{6}$$

Integrating the system of equations (5), preliminarily substituting the velocity expressions from system (4) into the last one and replacing *dt* with the right-hand side of equation (6), it was found the equation for determining the coordinates of the point M_n at a certain time. In this case, the limits of integration for the curvilinear section of the pulling stream will be from φ_o to $\varphi_0 + \alpha$, i.e. $\varphi_n \in [\varphi_0; \varphi_0 + \alpha]$ (fig.3).

Finally, when the stalk of flax passes along the pulling stream, the coordinates of the point M_n are equal to:

$$\left.\begin{aligned} X_n &= R\left[\cos\beta\left(\sin\varphi_n - \sin\varphi_0\right) + {}^{V_m}\!/_{V_p}\left(\varphi_n - \varphi_0\right)\right] + X_0, \\ Y_n &= R\left(\cos\varphi_n - \cos\varphi_0\right) + Y_0, \\ Z_n &= R\sin\beta\left(\sin\varphi_n - \sin\varphi_0\right) + Z_0. \end{aligned}\right\} \tag{7}$$

In the equations of system (7), the quantities X_o, Y_o, Z_o are constants of integration and correspond to the coordinates of the point *A* of the beginning of the section of the *AB* curve considered in space.

As the origin of coordinates of the *XOYZ* spatial system, the point of placement of the flax stalk in the soil, which falls vertically into the mouth of the pulling stream (fig.4), was chosen. At the same time, the coordinates of point *A* are: X_0=0; Y_0=0; Z_0=*h*, where *h* - the height of the starting point of pulling.

Due to its design features, the pulling apparatus interacts with flax stalks during gleaning in such a way that the pass performs only part of the energy of pulling out the stalks. The rest of the energy is performed due to the portable translational movement of the machine.

The power used in this case is determined by the formula (*Yukhymchuk et al., 2021*):

$$N = N_p + N_m = TV_p\cos\left(\bar{T},\bar{V}_p\right) + TV_m\cos\left(\bar{T},\bar{V}_m\right) \ , \tag{8}$$

where: N_p and N_m - powers transmitted to the pulling disc and the machine for pulling the stalk out of the soil;

T - the force of pulling the flax stalk out of the ground;

$\bar{T}\bar{V}_p$ and $\bar{T}\bar{V}_m$ – the angles between the force vectors *T* and the speeds of the conveyor belt V_p and the aggregate V_m.

The force vector *T* is directed along the stalk in the direction of its extension (fig.4b).

The strength of *T* depends on many factors (properties of the soil, type of flax, characteristics of flax stalks, stalk density) and is determined experimentally. The value of this force *T* changes as the stalk root is pulled out of the soil. One of the most characteristic dependences of the force *T* on the length of the stalk extension $\Delta\rho$ is parabolic (*Yukhymchuk et al., 2021*), according to which the force *T* increases with an increase in $\Delta\rho$, reaches a maximum (T_{max}) and falls.

The formula for this dependence is as follows:

$$T = 4T_{\max}\frac{\Delta\rho}{a}\left(1 - \frac{\Delta\rho}{a}\right) \tag{9}$$

where *a* - the length of the path of force action (the length by which the stalk needs to be pulled out of the soil until the root is completely detached).

As stated earlier by *Yukhymchuk et al., (2021)* T_{max}=5 N, *a*=0.05 m. It is also made the assumption that the angle of inclination of the stalk during harvesting does not affect the value of T_{max}.

To ensure complete extraction of the flax stalk from the soil, the following conditions must be met:

$$\left.\begin{aligned} &a \le \rho_n - \rho_0, \\ &\rho_0 = \sqrt{\left(X_0 - X\right)^2 + \left(Y_0 - Y\right)^2 + Z_0^{\,2}}, \\ &\rho_n = \sqrt{\left(X_n - X\right)^2 + \left(Y_n - Y\right)^2 + Z_n^{\,2}}. \end{aligned}\right\} \tag{10}$$

where ρ_0 - the distance from the point $M_o(X_o; Y_o; Z_o)$ - the starting point of stalk pinching in the pulling stream ($M_o \equiv A$) to the point *O*(*X*; *Y*; *Z*) - the location of the stalk root in the soil;

ρ_n - the distance from the point $M_n(X_n; Y_n; Z_n)$ the pinching point of the flax stalk when it is in the pulling stream, to the point *O*(*X*; *Y*; *Z*).

Figure 4b shows the position of the pulling disk after some time *t*. During this time, the pulling apparatus moved to a distance equal to $V_m t$, and the pulling disc under the influence of the pulling pass turned to the angle $\varphi = V_p t / r$. At the same time, clamped at the point M_n with coordinates (X_n; Y_n; Z_n), the flax stalk forms the corresponding angles with the coordinate axes: angle γ with the *OX* axis, angle δ with the *OY* axis, and angle ε with the *OZ* axis.

The location in the soil of the root part of the stalk is determined by point *O* with coordinates (*X*; *Y*).

The following vectors emanate from the point M_n: *T*, *V*, V_m, V_p, where *V* is the vector of the absolute speed of movement of the point M_p in space $V=V_m+V_p$. The projections of the vector V_p onto the coordinate axes (fig. 4b) V_{px}, V_{py}, V_{pz} are based on the equations of system (4).

From fig. 4b, it can be seen that the vectors of these projections form the same angles with the flax stalk as the corresponding coordinate axes. Then equation 8 will take the form:

$$N = N_p + N_m = T\left(V_{px}\cos\gamma + V_{py}\cos\delta + V_{pz}\cos\varepsilon\right) + TV_m\cos\gamma \tag{11}$$

From the right-angled triangle OCM_n (fig.4, b) $OM_n = \rho_n$ – the distance from point M_n to point *O*, which is determined by the system of equations (10), and $OC=X_n - X$. From here:

$$\cos\gamma = \frac{OC}{OM_n} = \frac{X_n - X}{\rho_n} \; . \tag{12}$$

Similarly, from the triangle ODM_n:

$$\cos\delta = \frac{OD}{OM_n} = \frac{Y_n - Y}{\rho_n} \; . \tag{13}$$

And from the OEM_n triangle:

$$\cos\varepsilon = \frac{OE}{OM_n} = \frac{Z_n}{\rho_n} \; . \tag{14}$$

By substituting expressions for their calculations (12), (13) and (14) into equation (11) instead of its corresponding elements, a system of equations for power calculation is obtained:

$$\left.\begin{aligned} N_P &= T\left(V_{px}\frac{X_n - X}{\rho_n} + V_{py}\frac{Y_n - Y}{\rho_n} + V_{pz}\frac{Z_n}{\rho_n}\right), \\ N_m &= TV_m\frac{X_n - X}{\rho_n}, \\ N &= N_p + N_m. \end{aligned}\right\} \tag{15}$$

According to equations (15), using formulas (9), (4), (7), (10) to find their elements, in order to quickly obtain the results of calculations based on various possible combinations of initial parameters, a computer program was developed in the computer system Maple algebras. This program allows you to monitor the change in power *N* and the distribution of its components N_p and N_m from the rotation of the pulling disc to the angle $\varphi_n \in [\varphi_0; \varphi_0 + \alpha]$ when pulling stalks with the corresponding *X*, *Y* coordinates of the points of the location of the roots. At the same time, it was taken into account that the stalk is picked under the condition:

$$0 \le \rho_n - \rho_o \le a \tag{16}$$

At $\Delta\rho > a$, the flax stalk is fully pulled out (*N*, N_p and N_m are equal to zero).

At the same time, the values of the parameters were as follows: the maximum value of the pulling force T_{max}=5 N; the length by which the stalk needs to be pulled out of the soil until the root is completely detached *a*=0.05 m; radius of the pulling disk *R*=0.16 m; the height of the starting point of harvesting *h*=0.2 m; the angle β of inclination of the receiver to the horizon was $\pi/3$, $\pi/4$ and $\pi/9$; angles $\varphi_0 = -\pi/6$, $\alpha = \pi/2$; circular speed of the pulling disk V_p=2.35 m/s; the speed of the car V_m was 1.18 m/s, 2.01 m/s and 2.47 m/s.

The resulting graphs of the component capacities using the Maple computer program were processed in another graphic computer program, Kompas. For clarity, using equation (3), it was changed from angular dimensions to linear dimensions, that is, along the abscissa axis, at the price of a division of 0.01 m, the length of the pulling stream zone *l*, which is involved in pulling the stalk, was set aside.

In this program, it is possible to find the energy, which goes to pulling the stalk - A, as well as the energy, which is performed by the pulling disc - A_p, and the energy, which is due to the traction force of the flax harvester - A_m. Graphically, the energy A, as well as its components A_p and A_m, are the areas of the figures formed by the corresponding curves of dependence N, as well as N_p and N_m and the abscissa axis (the length of the breech zone) divided by V_p. The formulas for calculating A, A_p and A_m are as follows:

$$\left.\begin{aligned} A &= \int_0^t N dt = \frac{1}{V_P}\int_0^l N dl, \\ A_P &= \frac{1}{V_P}\int_0^l N_P dl, \\ A_m &= \frac{1}{V_P}\int_0^l N_m dl. \end{aligned}\right\} \quad (17)$$

where t is the time during which the stalk is completely pulled out of the soil; l - the length of the pulling furrow zone, which is involved in pulling the stalk.

RESULTS AND DISCUSSION

In fig.4, the possible zone of the location of the roots of the stalks in the soil, which fall into the mouth of the pulling stream, is indicated by a dotted line. Let's consider three possible cases of stalks hitting the mouth of the pulling stream: when the stalk is tilted in the direction of movement of the flax pulling machine, when it is placed vertically, and when it is tilted in the direction opposite to the movement of the machine (fig.5). The central most inclined stalk has the X coordinate, which is $X = -h \cdot tg\beta = -0.2 \cdot tg60^0 = -0.341$ m.

For the stalk, which at the moment of clamping in the pulling stream was tilted in the direction of the flax pulling machine (coordinates of the location of its root in the soil were X=-0.341 m, Y =0 m (fig. 5a)) extraction from the soil occurs mainly according to due to the traction power of the machine N_m and only a small part is due to the drive power of the pulling disk N_p.

For the stalk, which was placed vertically at the time of being clamped in the grab rail (coordinates of the location of its root in the soil were X=0 m, Y =0 m (fig. 5b)), extraction from the soil occurs in the opposite way, mainly due to the power of the pulling disk N_p. and only a small part is due to the traction power of the N_m machine.

And for the stalk, which at the moment of being clamped in the pulling stream was tilted opposite to the direction of movement of the flax pulling machine (the coordinates of the location of its root in the soil were X=0.341 m, Y =0 m (fig. 5c)) extraction from the soil occurs only due to power of the drive of the pulling disk N_p, which is greater than the power N of pulling the stalk out of the ground, and the traction power of the machine N_m takes a negative value. That is, part of the power of the pulling apparatus through the stalk is spent on moving the machine - the so-called phenomenon of power circulation. Also from this fig. 5, it can be seen that for this stalk, the length of the pulling zone, which is involved in pulling the stalk, increases to 0.17 m.

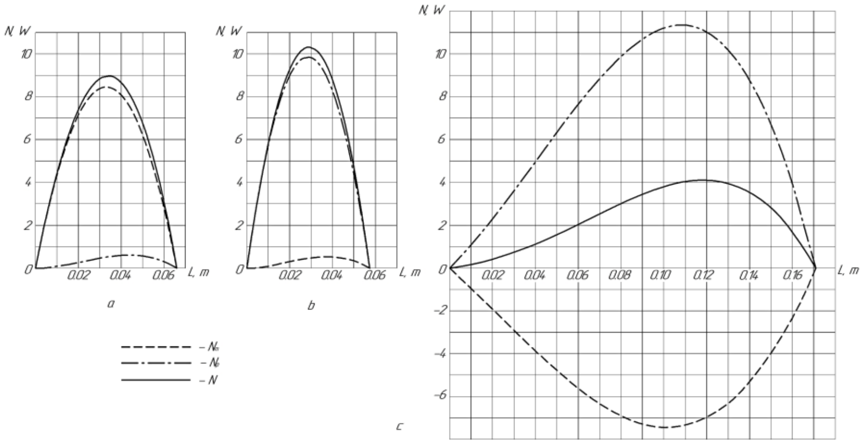

Fig. 5 - Power distribution during stalk pulling depending on the initial inclination of the flax stalk at V_m=2.01 m/s, $\beta = 60^0$

a – coordinates of the stalk root X=-0.341 m, Y =0 m, A_m=0.157 J, A_p=0.009 J, A=0.166 J;
b – coordinates of the stalk root X=0 m, Y =0 m, A_m=0.007 J, A_p=0.159 J, A=0.166 J;
c – coordinates of the stalk root X=0.341 m, Y =0 m, A_m=0.506 J, A_p=-0.340 J, A=0.166 J

The influence of the forward speed of the flax harvester on the distribution of the components of the power involved in pulling the stalk out of the ground was also analysed (fig. 6).

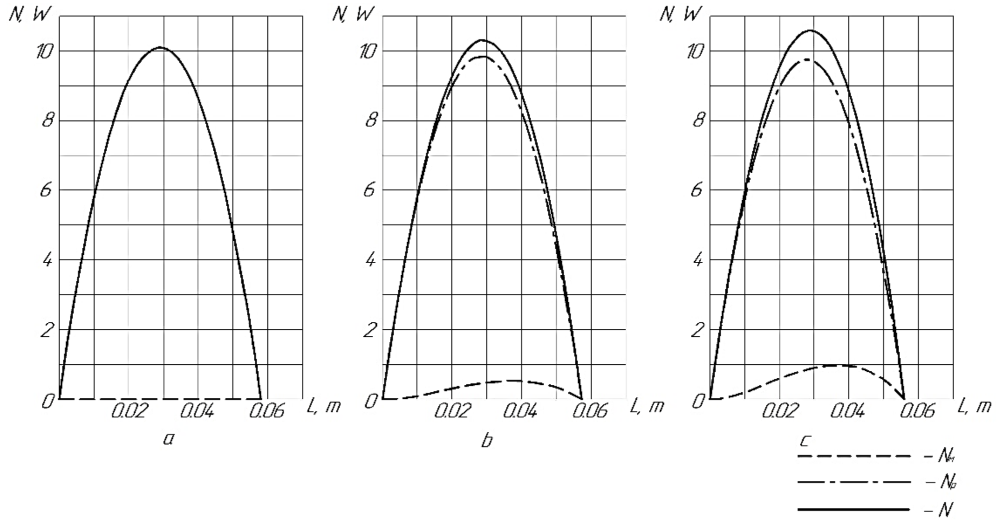

Fig. 6 - Power distribution during stalk pulling depending on the forward speed of the flax harvester at the stalk root coordinates X=0 m, Y =0 m

a – V_m=1.18 m/s, A_m=0 J, A_p=0.166 J, A=0.166 J;
b– V_m=2.01 m/s, A_m=0.007 J, A_p=0.159 J, A=0.166 J;
c – V_m=2.47 m/s, A_m=0.013 J, A_p=0.153 J, A=0.166 J

To do this, consider a stalk that enters the pulling stream vertically, that is, the coordinates of the root of the stalk *X*=0 m, *Y* =0 m (fig.6).

At the speed of the flax pulling machine V_m=1.18 m/s (fig.6a), the power *NM* from the movement of the machine is zero, and the graph of the power of the pulling disk N_p coincides with the graph of the power *N* for pulling the stalk out of the ground, that is, the stalk is pulled only under the action capacity of the pulling apparatus.

When the speed increases to V_m=2.01 m/s and to a speed of 2.47 m/s, it can be seen that when pulling the stalk out of the ground, the traction power N_m of the movement of the machine is already engaged and its share increases with the increase in the forward speed of the machine V_m.

Also, depending on the use of the pulling apparatus (installed on a flax winch or on a flax harvester), different angles of inclination of the pulling apparatus to the horizon are possible. Let's analyse how the angle of inclination of the pulling apparatus to the horizon affects the distribution of power when pulling the stalk out of the ground. To do this, consider a stalk that enters the pulling pit vertically, that is, the coordinates of the root of the stalk are *X*=0 m, *Y* =0 m. The speed of the machine is V_m=2.01 m/s, the angle of inclination of the pulling apparatus to the horizon is 60^0, 45^0 and 20^0 (fig.7).

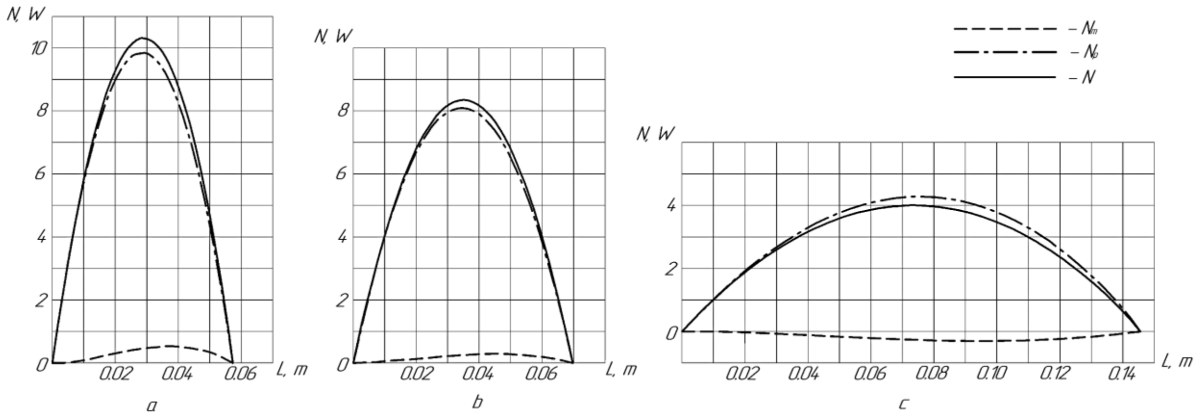

Fig. 7 - Power distribution when pulling a stalk depending on the angle of inclination of the pulling apparatus to the horizon with the coordinates of the root of the stalk *X*=0 m, *Y* =0 m, V_m=2.01 m/s

a – $\beta = 60^0$, A_m=0.007 J, A_p=0.159 J, A=0.166 J;
b – $\beta = 45^0$, A_m=0.005 J, A_p=0.161 J, A=0.166 J;
c – $\beta = 20^0$, A_m=-0.011 J, A_p=0.177 J, A=0.166 J

From the considered cases in fig.7, it can be seen that for the stalk that enters the picker vertically, it is pulled out of the soil mainly due to the power of the picker disk. When the angle of inclination of the harvester to the horizon is reduced, the share of traction power from moving the machine to pulling the stalk from the soil decreases. And for the case in fig.7c, it can be seen that the power takes negative values and part of the power of the pickup apparatus is spent on moving the machine - the phenomenon of power circulation described above. In addition, from the graphs in fig.7, it can be seen that when the angle of the pulling apparatus to the horizon is reduced, the length of the pulling stream zone, which is involved in pulling the stalk, increases from 0.057 m to 0.145 m.

As the calculations showed, the energy of pulling does not depend on the location of the stalks in the elementary bundle and in all cases is equal to A = 0.166 J.

In one second, the number of stalks n_s equal to:

$$n_s = B\ V_m\ t\ i \tag{18}$$

In our case, at B = 1.5 m, V_m= 2.01 m/s, t = 1 s, assuming i = 1600 stalks/m^2, it is obtained that J_c = 4824 stalks are selected in 1 second. Then the energy per second of pulling A_s will be equal to:

$$A_s = A \cdot n_s = 0.166 \cdot 4824 = 808.8 \text{ J.} \tag{19}$$

Flax stalks, which come to the pulling stream, are tilted by the side bars of the dividers in the direction of the machine, or as the central stalks are clamped vertically. If the power distribution graphs (fig. 4a, 4b) for an inclined and vertically standing stalk are considered, one can follow the following relationship: more inclined stalks are pulled out of the ground due to the traction power from the movement of the flax harvester, and less inclined stalks - under the action of the rotation of the pulling disc. Therefore, it can be assumed that in the general pulling of stalks, half of the power comes from the traction power of the movement of the flax pulling machine, and half - from the power of the pulling apparatus.

The spent energy was calculated: A_{ps}= 400 J; A_{ms} = 400 J.

CONCLUSIONS

The design of the disc-belt flax-pulling apparatus is proposed, which will increase the durability of the pulling belts and reduce the material consumption of the flax gleaning machine. The geometrical parameters of the pulling section of the disc-belt flax-pulling apparatus have been established. The energetics of the process of picking flax stalks, which are clamped in the curved longitudinal pulling stream of the disc-belt flax-pulling apparatus, have been theoretically investigated. The dynamics of changes in the components of pulling power when moving the flax stalk along the pulling stream were studied, depending on: the initial inclination of the flax stalk, the forward speed of the flax harvester, the angle of inclination of the pulling apparatus to the horizon. The energy per second of pulling and the value of its components are determined.

Graphical dependences of the distribution of pulling power between the loading of the disk-belt pulling apparatus and the traction force of the machine are given, depending on: the initial inclination of the flax stalk, the forward speed of the flax harvester, the angle of inclination of the pulling apparatus to the horizon. Calculations confirmed that the selected parameters of the apparatus fully satisfy the requirements of the pulling process. The pulling energy does not depend on the initial angle of inclination of the stalk and is equal to 0.166 J in all cases.

This design of the disc-belt pulling apparatus is at the design stage - drawings of assembly units and parts are being developed. This design is new, so the authors will be very grateful for comments and suggestions for its improvement.

REFERENCES

[1] Abdel-Wahab M. K., El-Sharabasy M. M. A. & El-Didamony M. I. (2012) Development and performance evaluation of a pulling flax machine. *Misr Society of Agricultural Engineering. (Farm machinery and power)* 29(3) Vol. 45, No. 3, 2012 pp. 973–992. https://www.academia.edu/105738184/Development_and_Performance_Evaluation_of_a_Pulling_Flax_Machine

[2] Bourmaud, A., Gibaud, M., & Baley, C. (2016). Impact of the seeding rate on flax stem stability and the mechanical properties of elementary fibres. *Industrial Crops and Products*, 80, 17-25. https://doi.org/10.1016/j.indcrop.2015.10.053

[3] Charney Madeleine (2014) Flax: Food and Fiber. *Journal of Agricultural & Food Information* Volume 15, 2014 - Issue 4 pp, 249-254. https://doi.org/10.1080/10496505.2014.952575

[4] Dudarev, I., Zabrodotska, L., Kirchuk, R., & Taraymovich, I. (2014) Reasoning on parameters of roller with spiral groove of flax pulling mechanism (Обґрунтування параметрів вальця з гвинтовим пазом льонобрального апарата). *INMATEH Agricultural Engineering*, 2014, 42(1), pp. 49–54. https://inmateh.eu/volumes/pdfs/8.pdf

[5] Dudarev I. (2015). *Theoretical bases for the modernization of flax production machines (Теоретичні основи модернізації машин для виробництва льону)***.** Monograph. Lutsk State Technical University, Lutsk, 268. Ukraine. ISBN 978-617-672-115-4 301

[6] Dudarev, I. (2020). A review of fibre flax harvesting: conditions, technologies, processes and machines. *Journal of Natural Fibers* (in press). http://doi.org/10.1080/15440478.2020.1863296

[7] Dudarev, I., & Say, V. (2020). Development of resource-saving technology of linseed harvesting. *Journal of Natural Fibers*, 17(9), pp. 1307-1316. https://doi.org/10.1080/15440478.2018.1558161

[8] Dudarev, I., & Khomych, A. (2022). Low-quality flax straw biomass harvesting for subsequent use as fuel: a review. *Agricultural Machines*, 48, 15-29. Ukraine. https://doi.org/10.36910/acm.vi48.779

[9] Goudenhooft, C., Alméras, T., Bourmaud, A., & Baley, C. (2019). The remarkable slenderness of flax plant and pertinent factors affecting its mechanical stability. Biosystems Engineering, 178, 1-8. https://doi.org/10.1016/j.biosystemseng.2018

[10] Hall, L.M., Booker, H., Siloto, R.M.P., Jhala, A.J., Weselake, R.J. (2016). Flax (Linum usitatissimum L.). *Industrial Oil Crops*, 157-194. https://doi.org/10.1016/B978-1-893997-98-1.00006-3

[11] Jhala, Amit J. & Hall, Linda M. (2010) Flax (*Linum usitatissimum L*.): Current Uses and Future Applications. *Australian journal of basic and applied sciences* 4(9):4304-4312

[12] Karg, Sabine. (2022) "Flax seeds from Neolithic and Bronze Age pile-dwelling sites in Europe" *Praehistorische Zeitschrift*, vol. 97, no. 1, 2022, pp. 90-109. doi.org/10.1515/pz-2022-2036

[13] Lafond, G. P., Irvine, B., Johnston, A. M., May, W. E., McAndrew, D. W., Shirtliffe, S. J., & Stevenson, F. C. (2008). Impact of agronomic factors on seed yield formation and quality in flax. *Canadian Journal of Plant Science,* 88, 485-500.

[14] Mańkowski, J., Maksymiuk, W., Spychalski, G., Kołodziej, J., Kubacki, A., Kupka, D. & Pudełko, K. (2018) Research on New Technology of Fiber Flax Harvesting. *Journal of Natural Fibers*. 2018. Vol. 15, Issue 1. pp. 53–61. doi: https://doi.org/10.1080/15440478.2017.1302390

[15] Nag, S., Mitra, J., & Karmakar, P. G. (2015). An overview on flax (Linum usitatissimum L.) and its genetic diversity. *International Journal of Agriculture, Environment and Biotechnology*, 8(4), 805-817.

[16] Omer, T. A., Amal, M. A. El-Borhamy, & Maysa, S. Abd. El-Sadek. (2020). Effect of harvesting dates and seeding rates on yield and yield components of some flax varieties. *Journal of Plant Production*, 11(12), 1501-1505. https://doi.org/10.21608/jpp. 2021.55272.1012

[17] Pisupati, A., Willaert, L., Goethals, F., Uyttendaele, W., & Park, C. H. (2021). Variety and growing condition effect on the yield and tensile strength of flax fibers. *Industrial Crops and Products*, 170, 113736. https://doi.org/10.1016/j.indcrop.2021.113 736

[18] Soucek, J., Sturc, T., Marecek, J. (2017). Analysis of linseed production with use of flax puller and combine harvester for its harvest. *Acta Univ. Agric. Silvic. Mendelianae Brun*, 65, 511-517.

[19] Yaheliuk, S., Didukh, V., Busnyuk, V., Boyko, G., & Shubalyi, O., (2020), Optimization on Efficient Combustion Process of Small-Sized Fuel Rolls made of Oleaginous Flax Residues. *INMATEH – Agricultural Engineering*, 62(3), pp. 361–368. Romania. https://doi.org/10.35633/inmateh-62-38/

[20] Yang, R.B., Li, X.J., Tan, S.L. (2009). Development survey and prospect of flax industry. *Modern Agricultural Sciences*, 4. http://en.cnki.com.cn/Article_en/CJFDTOTAL-NCSY200904121.htm

[21] Yukhymchuk, Sv., Yukhymchuk, S., Tolstushko, M., & Datsyuk, L. (2021). Energetics pulling of the flax stalks by pulling apparatus with rectlinear transversal streams (Енергетика брання стебел льону бральним апаратом з прямолінійними поперечними рівчаками). *Scientific notes (Наукові нотатки)*, Vol. 72, pp. 145-150, Ukraine. https://doi.org/10.36910/775.24153966.2021.72.21

[22] Yukhymchuk, Sv., Tolstushko, M., Yukhymchuk, S., & Datsyuk, L. (2022). Development of the design of a disc-belt flax-pulling device. (Розробка конструкції дисково-пасового льонобрального апарата) *Scientific notes (Наукові нотатки)*, Vol. 73, pp. 239-242, Ukraine. https://doi.org/10.36910/775.24153966.2022.73.35

[23] Zając, T., Oleksy, A., Klimek-Kopyra, A., & Kulig, B. (2012). Biological determinants of plant and crop productivity of flax (Linum usitatissimum L.). *Acta Agrobotanica*, 65(4), 3-14.
[24] Zuk, M., Richter, D., Matuła, J., & Szopa, J. (2015). Linseed, the multipurpose plant. *Industrial Crops and Products,* 75, Part B, 165-177. https://doi.org/10.1016/j.indcrop.2015.05.005