1. Introduction

One of the most important, time-consuming, and responsible operations during soil preparation in the autumn period is plowing. It is necessary to plow the remains of stems of agricultural crops, which are organic fertilizers, as well as to accumulate moisture in soil over a winter-spring period for obtaining a stable harvest of agricultural produce.
2. Literature review and problem statement

Paper [1] emphasized that the reversible ploughs ensure smooth plowing without a separated furrow. Such manufacturers of agricultural machinery as «Lemken», «Rverneland» or «Vogel Noot» design the mounted and attached ploughs with a wide range of plough casings. Ploughs differ in a capture width, the shape and type of a ploughshare surface, specialized devices intended to help a plough’s casing to bypass obstacles in the form of stones. However, one of the parts of a plough’s casing, a landside, has remained unaffected by structural changes. The sliding friction force between a wall of the furrow and a landside leads to the increased traction force of a plough and to increasing the energy intensity of a ploughing unit [1]. It is not possible to abandon a landside because, despite the simplicity of its design, it plays an important role: preventing the displacement of a plough’s casing towards the side of the wall of the furrow. The soil response from the wall of the furrow neutralizes the lateral pressure of a layer caused by the non-symmetry of a plough’s casings. It was determined that that each landslide in the plough PLN-3-35 is exposed to a transverse force of 1 kN, which presses against the wall of the furrow. This leads to a wear of a landside; in addition, the existence of this force gives rise to the soil compaction of the lateral wall of the furrow; thereby breaking its structure, which generally enhances the energy efficiency of the process of cultivation.

Calculating the traction force of a plough mostly employs a Goryachkin formula [2, 3]. The formula takes into consideration the impact on the magnitude of the traction resistance of a plough exerted by its weight G, cultivation depth a, capture width b, soil properties k, and the motions speed of a plough v. However, this formula in its implicit form does not account for the impact on the magnitude for force P exerted by the friction of landsides against the walls of a furrow. However, paper [2] stressed that it is necessary to further refine the individual members of this formula. The sliding friction forces that occurs between landsides and the walls of a furrow were almost neglected; it was mistakenly believed that its magnitude is negligible. Therefore, it is necessary to improve a plough’s landside, to search for more efficient, modern working bodies for machines involved in soil cultivation.

There are experimental samples of two- and three-casing ploughs, in which, to reduce the wear resistance of a plough’s landsides, each casing was supplemented with the rubber rolls, installed horizontally to the bottom of a furrow, with the possibility to adjust them relative to the wall of the furrow. The data on experimental study indicate that a plough’s casing with a supporting rubber roll, installed horizontally, demonstrated traction resistance that was 12% less than that for a plough’s casing with a landside [4].

Paper [5] reported results from a theoretical study into determining the traction resistance of a two-casing plough with a supporting rubber roller. This roller is mounted horizontally to the bottom of a furrow at the second casing and without a landside at the first casing of the plough. The research results have shown that the traction resistance of the improved plough was 9.3% less than the traction resistance of a standard plough with a landside.

To reduce wear of the most wearable sections in parts of the working bodies of a plough’s casings during tilling, it was proposed to make openings in a landside. The axes of the landsides’ openings are mounted at an angle in the form of a cut cone [6]. This leads to a decrease in the traction resistance of a plough.

To reduce the energy intensity of the mounted ploughshare PLN-3-35, we installed a furrow wheel after each plough’s casing on a leash. Each wheel is pivotally attached to the guide at an angle of α = 25–45° to the bottom of the furrow. As the studies have shown, specific fuel consumption with experimental furrow wheels, mounted after each casing of the mounted plough, decreased by 16–21% [7, 8].

It was proposed to install a drive mechanism in the form of a hydraulic motor on each wheel of a plough. The energy tool is linked through the mechanism of control that enhances performance by increasing the stability of a ploughing unit and reducing the traction effort required to move during operation [9]. Such an mechanism increases the complexity and cost of the structure and, at the same time, reduces reliability.

One of the effective techniques is to abandon a standard landside and replace it with a cylindrical drum. The drum is arranged based on the height of the casing’s recess into soil with a vertical axis of rotation, which could reduce the magnitude of friction forces and the cost of fuel and lubricants [10].

Replacing a landside with a flat-rounded element with the vertical axis of rotation in the form of a disk knife, located at the lower part of a bearer, made it possible to reduce the energy consumption by a plough’s casing [11]. In order to reduce sliding of the flat-rounded element along the wall of a furrow and to prevent its deflection, it is proposed to apply, at a depth of a ploughshare, a disk knife with notches. A disk knife is set at an angle in the direction of displacement of a ploughshare. As the studies have shown, specific fuel consumption with experimental furrow wheels, mounted after each casing of the mounted plough, decreased by 16–21% [7, 8].

One of the effective techniques is to abandon a standard landside and replace it with a cylindrical drum, which could reduce the magnitude of friction forces. The choice of structural and technological parameters for a cylindrical drum depends on a series of operational and soil-climatic conditions. The derived theoretical dependences make it possible to determine the radius of the drum of a cylindrical landside and the magnitude of leverage for the action of force from a supporting reaction from the side of the wall of a furrow to balance the casing of a plough [14].

In order to prolong the mean time between failures for a standard landside, the mounted ploughs of furrow series PLN-3-35, PLN-4-40, and PLN-5-40 are produced. Atop the back end of landsides are the plates the size of 0.16 m in width, 0.13 m in length, and a thickness of 0.018 m. That makes it possible, in case of its wear, to replace, rather than landsides, these plates only.

Papers [15, 16] report results from experimental studies of a ploughing unit, which established dependences of the largest specific performance of general-purpose ploughs on speed. However, the papers considered the high-speed modes, which are not typical for plowing units, that is, the translational speed of a plough’s casing must be within 1–3 m/s.

In a study conducted with the use of a coating, made from fluoroplast, on the working surface of plough’s casing, the coating made it possible to reduce the energy intensity of plowing process by 55% [16]. Application of steel, cast iron, surfacing, ceramic and composite materials, also reduces the energy intensity of plowing process [17].
Plowing the soil is the most energy-intensive operation in plant agriculture. It was determined that reducing the power consumed by a ploughshare, as the most loaded working tool of the plough, could be achieved by oscillations or by changing its parameters [19].

That is, improvement of plough’s casings is addressed by a series of scientists, however, there are no comprehensive solutions to the task on constructing a family of plough casings for different conditions of their use. The issue on reducing the traction resistance of working bodies in soil has been also addressed. Summing up the above, one can draw the following conclusions:

– not enough attention has been paid to the influence of a transverse force of pressure acting on the plough’s landsides;

– not enough attention has been paid to determining the magnitude for the traction effort of each link in the mechanism of a tractor unit’s attachment because designing a strain-gauge mechanism for an attachment requires considerable expenses;

– there are no technical solutions aimed at overcoming such a technological disadvantage, characteristic of a landside, as the existence of a sliding friction force along the wall of a furrow, which leads to the increasing traction effort of a tractor unit, thereby increasing the cost of fuel and lubricants when while tilling the soil.

Therefore, it is a relevant task to resolve a scientific-applied task on determining the impact of structural and operational parameters on energy consumption by a plough.

### 3. The aim and objectives of the study

The aim of this study is to define directions for reducing the energy intensity of a mounted plough (using the mounted plough PLN-3-35 in an assembly with the tractor MTZ-82 as an example).

To accomplish the aim, the following tasks have been set:

– to conduct an experimental study into determining the dependence of transverse force on the speed and location of a landside;

– to undertake an experimental research into determining the dependence of traction efforts of each link at a tractor’s attachment on motion speed;

– to substantiate the ways for reducing the energy intensity of the plough.

### 4. Materials and methods of the study

#### 4. 1. A measuring system and the arrangement of strain gauges at a landside and on the links in the mechanism of a tractor’s attachment

Conducting an experimental study under field conditions aimed at determining the traction characteristics of a plough employs different measuring systems [16, 17, 20, 21].

We applied the system for measuring the dynamics and energy of mobile machines (SMDEMM), which refers to the technical instruments for diagnosing and operational control and can be used in agriculture. The measuring system is intended for determining the kinematic, dynamic, power, and energy characteristics for mobile machines and their elements in field tests [22, 23]. A principal diagram of SMDEMM is shown in Fig. 1.

Main components in the measuring system (Fig. 1) are a computing module, sensors, and a power supply unit. The computing module is intended for processing, visualization, and storing data acquired from the sensors. The power supply unit enables the measuring system to work autonomously or receive power from an on-board system of the unit.

#### 4. 2. Calibration of strain-gauge equipment

For calibrating the strain sensor mounted on the links in the mechanism of a tractor’s attachment and a landside, we used a laboratory bench. The bench makes it possible to consistently connect a calibrated dynamometer to links in the mechanism of a tractor’s attachment and a landside, to apply the required load and to maintain it over a long period of time. A model dynamometer that was selected was DPU-50-2, calibrated at NNTs Institute of Metrology (Kharkiv, Ukraine).
The calibration was performed for the strain gauge of a landside, the middle, right, and left links in a tractor’s attachment.

The dependence of a loading force on a landside on the codes of ADC is shown in Fig. 4. The dependence of a loading force on the middle link in the mechanism of a tractor’s attachment on the codes of ADC is shown in Fig. 5. The dependence of a loading force on the left link in the mechanism of a tractor’s attachment on the codes of ADC is shown in Fig. 6. The dependence of a loading force on the right link in the mechanism of a tractor’s attachment on the codes of ADC is shown in Fig. 7.

\[ P_i = -0.038i + 6024, \]  
\[ R^2 = 0.9957, \]  
(1)

where \( i \) are the codes of ADC.

The coefficient of determination for the strain gauge calibration results on a landside is equal to \( R^2 = 0.9957 \), indicating the existence of a dependence and its correctness.

For the middle link in the mechanism of a tractor’s attachment we have the following dependence of loading force and codes of ADC:

\[ P_i = -0.4615i + 63577. \]  
\[ R^2 = 0.9969, \]  
(2)

The coefficient of determination is equal to \( R^2 = 0.983 \), indicating the existence of a dependence and its correctness.

Finally, we have established the dependence of loading force on the right link in the mechanism of a tractor’s attachment and the codes of ADC, which takes the form:

\[ P_i = -1.0708i + 10257. \]  
\[ R^2 = 0.9856, \]  
(4)

The coefficient of determination is equal to \( R^2 = 0.9856 \), indicating the existence of a dependence and its correctness.

The hysteresis for strain gauges does not exceed 5%.

The study was carried out at the fields of Kharkiv oblast in November 2018. The soil is «plain black soil», the preceding crop is potatoes, the hardness of the soil in layers was, at the surface, 2.71 kPa, at a depth of 0.1 m – 3.03 kPa, and
at a depth of 0.2 m the hardness was 4.52 kPa. The moisture content of soil at the surface was 13.2 %, at a depth of 0.1 m – 15.9 %, and at a depth of 0.2 m it amounted to 16.1 %. The depth of ploughing was 0.25 m.

4.3. Experimental study into determining the transverse force of pressure and the traction effort of a plough

The strain sensor of a plough’s landside is connected to the first channel of ADC and hereafter referred to as $P_1$. The strain sensor at the middle link in the mechanism of an attachment is connected to the second channel of ADC – $P_2$, the left link – to channel 4 and is denoted as $P_4$ and the right link – to channel 3 and is denoted as $P_3$.

The plowing speed for the machine-tractor assembly was chosen to be 1.5 m/s; 2.5 m/s, and 3.0 m/s.

The overall physical appearance of the machine-tractor assembly consisting of the tractor MTZ-82 and the mounted ploughshare PLN-3-35 with the installed measurement system and sensors is shown in Fig. 8.

Fig. 8. Physical appearance of a machine-tractor assembly consisting of the tractor MTZ-82 and the mounted ploughshare PLN-3-35 with the installed measurement system and sensors

The physical appearance of the strain gauges mounted at the right, left, and middle links of the tractor’s attachment is shown in Fig. 9–11.

Fig. 9. The physical appearance of the strain gauge installed at the right link of the tractor’s attachment

Fig. 10. The physical appearance of the strain gauge installed at the left link of the tractor’s attachment

Fig. 11. The physical appearance of the strain gauge installed at the medium link of the tractor’s attachment

When conducting the experimental study, it was decided to install at the bearer of a third plough’s casing a landside with a strain sensor. The physical appearance is shown in Fig. 12, 13.

Fig. 12. The physical appearance of the tractor MTZ-82 with mounted ploughshare PLN-3-35 and a landside with the strain sensor mounted at the bearer of third casing of the plough

Fig. 13. The side view of a landside with the strain sensor mounted at the bearer of a third casing of the plough

5. Results of experimental research into the magnitude of transverse force of pressure on landsides and the traction efforts of a tractor’s attachment

Fig. 14 shows the general form of diagrams for transverse force $P_1$, which acts on the landside mounted at the bearer of a third casing of the plough.

The diagrams of traction efforts of each tractor’s attachment $P_2$, $P_4$ and $P_3$, at motion speed of the tractor assembly 1.5 m/s; 2.5 m/s; 3.0 m/s.

The arrangement scheme of sensors at the machine-tractor assembly when conducting an experimental study of the landside installed at the bearer of a second casing of the plough is shown in Fig. 15.
Fig. 16 shows the overall form of diagrams of transverse force $P_1$, which acts on the landside mounted at the bearer of a second casing of the plough at motion speed of the tractor assembly: $a = 1.5 \text{ m/s}$; $b = 2.5 \text{ m/s}$; $c = 3.0 \text{ m/s}$, and at traction efforts of each link in a tractor’s attachment $P_2$, $P_3$, and $P_4$.

Fig. 17 shows the diagrams of transverse force $P_1$, which acts on the landside mounted at the bearer of a second casing of the plough. Diagrams of the traction efforts of each tractor’s attachment $P_2$, $P_3$, and $P_4$, at motion speed of the tractor assembly 1.5 m/s; 2.5 m/s; 3.0 m/s.

Diagram of sensors arrangement at the machine-tractor assembly when conducting an experimental study of the landside installed at the bearer of a first casing of the plough is shown in Fig. 17.

Fig. 18 shows the general forms of diagrams for transverse force $P_1$, which acts on the landside mounted at the bearer of a second casing of the plough at motion speed of the tractor assembly: $a = 1.5 \text{ m/s}$; $b = 2.5 \text{ m/s}$; $c = 3.0 \text{ m/s}$, and at traction efforts of each link in a tractor’s attachment $P_2$, $P_3$, and $P_4$.
Fig. 16. Diagrams of transverse force $P_1$, which acts on the landside mounted at the bearer of a second casing of the plough at motion speed of the tractor assembly: $a - 1.5$ m/s; $b - 2.5$ m/s; $c - 3.0$ m/s, and at the traction efforts of each link in a tractor’s attachment $P_2$, $P_3$, and $P_4$.

Fig. 17. The physical appearance of the tractor assembly with the mounted ploughshare PLN-3-35 and the landside with the strain sensor installed at the bearer of a first casing of the plough.
5. Discussion of results of experimental study

The experimental study that we conducted has made it possible to define the transverse forces $P_1$ created by a landside when rotating a slice of soil acting on the landsides mounted at bearers of the casings of the plough PLN-3-35. It was established that depending on the location of the bearer of a plough along a diagonal beam the transverse forces $P_1$ that act on landsides accept different values and differ considerably from each other. The traction effort of each link in a tractor’s attachment $P_2$, $P_3$, and $P_4$ has made it possible to determine which of the links in a tractor’s attachment is loaded most, and which one bears the minimum load. The selected motion speeds of the tractor assembly have made it possible to define the dependences for a change in indicators.

It was established that the transverse force of pressure $P_1$, which acts on each landside of the mounted ploughshare PLN-3-35, differs significantly in its magnitude from each other depending on the motion speed of the tractor assembly. The magnitude of transverse force of pressure $P_1$ is also affected by the sequence of arrangement of a plough’s bearer along a diagonal beam.

Graphical dependence (Fig. 19, position 3) shows that the third landside is exposed to the mean transverse force of pressure $P_1$ from 1,848–1,871 N. There is a slight decrease in this force with increasing the speed of the tractor assembly.

![Graphical dependence](image-url)
As shown by the diagrams for Fig. 14, 16, 18, there is an intense impact of the surface of a landside against the wall of a furrow with peak loads of the transverse force of pressure $P_1$, which exceeds 2,100 N. It is explained by the fact that the third casing of the plough is set at the diagonal beam of the plough and is at a distance greater than 2 m from the axis of the attachment to the tractor assembly. The tractor assembly in the course of the study is not moving rectilinearly but intensely deviates to the right and to the left of the axis of ploughing; there is an intense rotation of it, which leads to a high-frequency impact of the landside against the wall of the furrow. This contributes to the increased wear of the surface of a landside. The graphical dependence also shows that with an increasing forward speed of the tractor assembly, the transverse force of pressure $P_1$ is reduced by an insignificant magnitude.

The second landside (Fig. 19, position 2) is exposed to transverse force of pressure $P_1$, which is within 1,522–1,604 N. As shown by the diagrams for $P_1$, the landside is pressed against the wall of the furrow and rotates both clockwise and counterclockwise in the direction of motion, together with a tractor assembly. This leads to the wear of the surface of a landside. The maximum value for force of pressure $P_1$ exceeds 1,900 N. The graphical dependence shows that with the increasing forward speed of the tractor assembly, the transverse force of pressure $P_1$ is gradually increasing.

Accordingly, the landside, which is set at the bearer of a first casing of the plough (Fig. 19, position 1) is exposed to the mean transverse force of pressure $P_1$, which initially accepts a larger value. With an increase in the motion speed of the tractor assembly, the force of pressure $P_1$ decreases, and it is within 1,610–1,668 N.

Since the mounted ploughshare PLN-3-35 is rigidly attached to the tractor’s attachment, its first casing follows the translational movement of the tractor. There is a heavy impact of the surface of a landside against the wall of a furrow; the maximum transverse force of pressure $P_1$ exceeds 2,400 N, which leads to the increased wear of the surface of a landside.

During our experimental field study of the mounted ploughshare PLN-3-35 to determine traction efforts $P_4$ of the left link in the mechanism of a tractor’s attachment (Fig. 22), it was found that the left link in a tractor’s attachment was almost underloaded. Its mean value is 4,097–4,342 N, and its maximal value amounts to 6,700 N. We can conclude that the left link in a tractor’s attachment is almost not loaded.

It is proposed to apply, instead of a standard landside for the mounted ploughshare PLN-3-35, a flat-rounded element in the form of a disk with a hub with a horizontal axis of rotation [24]. The disk converts the sliding friction forces into the rolling friction forces. Application of the disk leads to reducing the energy intensity of the plough by 13–15 %.
force tests. We have derived the diagrams of values for transverse characteristics of mobile machines and their elements under field determining the kinematic, dynamic, power, and energy cha-

ics and energy of mobile machines, which is designed for attachment
dynamometer of type DPU-50-2, calibrated at the NNTs
the	middle
casing	of	the	plough; 3 – the landside installed at
64
40
4
6
8
10
12
14
6. Conclusions

1. We have applied the system for measuring the dynami-
and energy of mobile machines, which is designed for
determining the kinematic, dynamic, power, and energy char-
acteristics of mobile machines and their elements under field
tests. We have derived the diagrams of values for transverse
force $P_1$ and the traction efforts of each link in a tractor’s
attachment $P_2$, $P_3$, and $P_4$ with an accuracy of ±2 %.
2. The application of the laboratory bench and the model
dynamometer of type DPU-50-2, calibrated at the NNTs

Fig. 22. Mean values for traction efforts $P_2$ acting
on the right link in a tractor’s attachment of the mounted
ploughshare PLN-3-35, depending on motion speed
of the machine-tractor assembly:
1 – the landside installed at the bearer of a first casing
of the plough; 2 – the landside installed at the bearer of
the middle casing of the plough; 3 – the landside installed at
the bearer of a third casing of the plough

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