EVALUATION OF ECONOMIC AND TECHNOLOGICAL INDICATORS OF THE COMBINED FRONTAL PLOUGH FOR SMOOTH PLOWING

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Introduction

No matter how much the technologies and technical means used in modern agriculture have improved, there are still problems that demand urgent solutions. Currently, particular emphasis is placed on the high energy expenditures during soil cultivation and on the mechanical degradation of the soil, which make the operation of agricultural machinery environmentally and economically inefficient. Modern agriculture views the creation and improvement of combined machines as a way to address these issues. In Armenia, specifically at the Armenian National Agrarian University, certain work has also been carried out in this direction [Esoyan et al., 2023]. However, like all combined machines, the proposed machine also requires further research and refinement.

Within the framework of this article, the equilibrium problem of the proposed combined machine has been examined, and based on experimental results the quality of work on slopes has been evaluated to outline the main directions for future improvements.

Methodology

The solution to the problem of machine balance aims not only to determine the forces acting on the machine but also to find solutions that will improve its performance. Naturally, this will contribute to reducing operating costs and increasing the economic efficiency of using the combined machine [Raish and Ugorov, 2000, 400].The equilibrium of the proposed machine was examined on flat terrain. Considering that the main component of this machine is a frontal plough that has undergone certain structural modifications, the problem was solved using the example of a traditional plow’s equilibrium. As is common in similar problems, several assumptions were made [Tonapetyan, 2004; Grigoryan et al., 1998, 320]:

1. The combined machine moves in a straight line at a uniform speed.
2. The working organs of the frontal plough and the disc harrow included in the combined machine’s composition enter the soil uniformly, while the third unit (the roller), which does not penetrate the soil, presses the soil uniformly across the entire working width. Naturally, each of these units is subject to resistance forces over the entire contact area

with the soil. For simplification, it was assumed that the entire resistance of each working organ is concentrated at a single point.

Under these assumptions, solving the equilibrium problem reduces to determining the support reactions in the vertical and horizontal planes [Tarverdyan et al., 2001, 349]. Moreover, the results obtained must satisfy the specified equilibrium conditions.

Literature Review

All the structural and working components of the proposed combined frontal plough [Esoyan et al., 2023] that "rest" on the soil during operation are aimed at ensuring the equilibrium of the machine. The reaction forces arising from contact with the soil help enhance the machine's stability. Generally, the greater these reaction forces, the higher the stability of the machine. Because the combined machine is considered mounted, its equilibrium problem is examined by analogy with mounted mechanisms [Meshcherski, 1990, 584; Tarverdyan et al., 2006, 425].

The forces acting on the three units of the combined machine were investigated, and the values of those forces that can be determined theoretically were found. The frontal plough is of a mounted type, attached to the tractor by a three-point linkage. It has two degrees of freedom: Rotation in the vertical-longitudinal plane (XOZ), Rotation in the horizontal plane (XOY) around a vertical axis [Grigoryan et al., 1998, 320; Sineokov and Panov, 1977, 328]. Accordingly, the force analysis was carried out in both planes. In the vertical plane, the following forces act on the combined machine [Yesoyan et al., 2023, 315–320]:

-$G_{c.m}$ (the weight force of the combined machine), which is the sum of three components: G_p (weight force of the plough), $G_{d.b}$(weight force of the disc battery), G_r (weight force of the roller). Therefore, $G_{c.m}= G_p+ G_{d.b}+G_{r.}$

- R_{xz} (the soil reaction force component acting on the plough bodies).
- F_{fr} (the frictional force between the plough bodies and the bottom of the furrow).
- R_d (the resistance force of the plough's disc coulters).
- P_{xz} (the traction force component of the combined machine).
- R_{wxz} (the reaction component of the frontal ploughs's support wheels).
- $R_{d.b}$ (the resistance on the disc battery).
- R_r (the resistance on the roller).

Using theoretical methods, the following values of some of these forces were obtained [Yesoyan et al., 2023, 315–320]:

G_p=9,8kN, $G_{d.b}$=0,8kN, G_r=0,6kN, $G_{c.m}$=9.8+0,8+0,6=11,2kN, R_{xz}=27,5kN, F_{fr}= 3,92kN, R_d=0,6kN, $R_{d.b}$ =4.32kN, R_r=1,2kN:

It is not possible, however, to determine the traction force component P_{xz} of the combined machine and the support wheel reaction component R_{wxz} theoretically. These two unknown forces can be found graphically, based on the known fact that their directions are known. The reaction of the wheel is directed at an angle of 120 degrees relative to the vertical (for medium-hard soils), and the traction force is directed along the line connecting the tractor's instantaneous center to the machine's center of gravity [Sineokov and Panov, 1977, 328]. By the same principle, the equilibrium of the combined machine in the horizontal plane is also considered. In this plane, the following forces act:

- R_{xy} (the soil reaction force component on the plow bodies).
- F_{fr} (the frictional force between the plough bodies and the bottom of the furrow).
- R_d (the resistance force of the plough's disc coulters).
- P_{xy} (the traction force component of the combined machine).
- R_{wxy} (the reaction component of the support wheels).
- $R_{d.b}$ (the resistance on the disc battery).
- R_r (the resistance on the roller).

In this case as well, certain force values were determined theoretically, specifically:
R_{xy}=28,5kN, F_{fr}= 3,92kN, $R_{d.}$=0,6kN, $R_{d.b}$ =4.32kN, R_r=1,2kN

Scientific novelty

As a result of solving the balance problem, the forces acting on individual working organs and the overall traction resistance of the combined machine have been determined. This enables the selection of an appropriately powered tractor within the aggregate, the formation of an optimal aggregate, and the establishment of optimal operating modes for different conditions. Consequently, this approach helps avoid unnecessary economic expenses [Trubilin et al., 2014, 654-672]. The traction force of the combined machine and the reaction of its support wheels have been determined by solving the equilibrium problem for the plough. The most suitable approach for this is a graphical method.

For that purpose, the structural diagram of the plough is drawn in two projections (Figure 1) using a certain scale. The vectors of the acting forces are placed on the diagram, then a force polygon is constructed, and the geometrical sum of the known forces is carried out. The forces can be summed in any order; however, in the final step, one must add the support reaction and the resultant of all the resistance forces (i.e., the traction force). Their magnitudes are unknown, but their directions are known.

According to the equilibrium condition, the force polygon must be a closed shape, and the resultant should pass through the instantaneous center of rotation of the system illustrated in Figure 2.

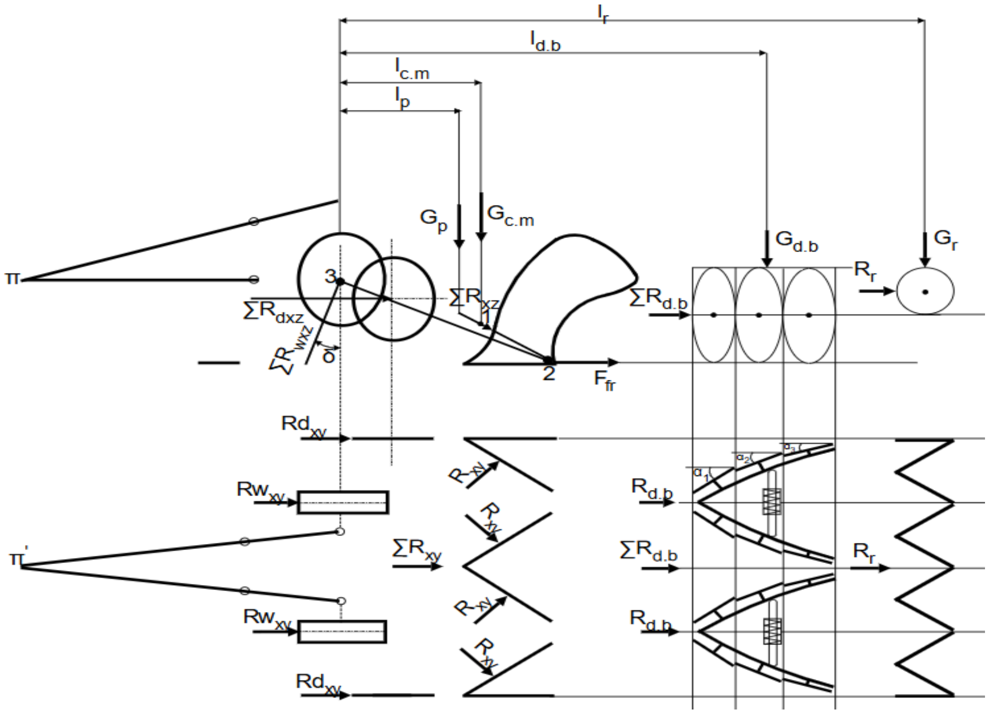


Figure 1. Schematic diagram for determining the traction resistance of the combined frontal plough using a graphical method.

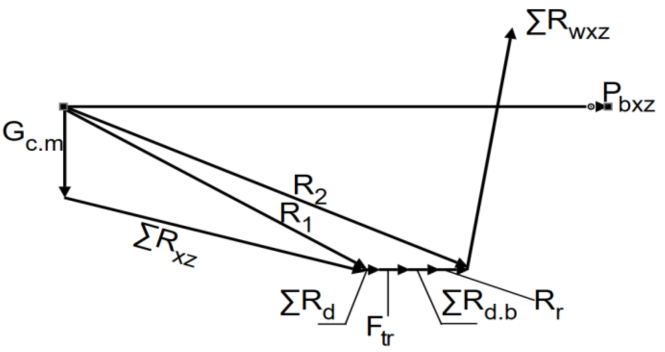


Figure 2. Force polygon for determining the traction resistance of the combined frontal plough.

Analysis

First, using the technological diagram of the combined machine, the coordinates of the point of application of the combined machine's total weight were determined. For this, the condition of equilibrium of the weight forces was set up [Esoyan et al., 2002, 81–87; Timofeev, 2023, 432].

$G_{c.m}*l_{c.m}= G_p*l_p+ G_{d.b}*l_{d.b}+ G_r*l_r$ (1) where

$l_{c.m}$, l_p, $l_{d.b}$, and l_r are the distances from the tractor to the center of gravity of, respectively, the combined machine, the frontal plough, the disc battery, and the roller. Taking into account that the structure of the machines in the examined system is symmetrical, it was assumed that the weight forces of the individual components of the combined machine are applied at their geometric centers. Consequently, the values of $l_{p,}$ $l_{d.b,}$ l_r were obtained through measurements.

Using the equilibrium condition (1), the distance of the combined machine's center of gravity from the tractor, denoted by $l_{c.m}$, was found:

$L_{c.m}=(G_p\times l_p+G_{d.b}\times l_{d.b}+G_r\times l_r)/G_{c.m.}$ (2)

On the force polygon, the weight of the combined machine is added to the resultant of the forces acting on the plow bodies, denoted by ΣR_x. This yields the force R_1.

In the vertical projection of the machine's diagram, the intersection point of those force directions is designated as point 1. From point 1 on the diagram, a line is drawn parallel to R_1 until it intersects the line of the friction force F_{fr} (between the plow bodies and the soil) at point 2.

On the force polygon, starting from the endpoint of R_1, the forces F_{fr}, ΣR_d, $\Sigma R_{d.b}$, and R_r are added head-to-tail. Connecting the endpoint of these vectors back to the start of the polygon gives their resultant, R_2 .

On the diagram of the combined machine, from point 2 a line is drawn parallel to R_2 until it intersects the line of the support-wheel reaction ΣR_{wxz} at point 3. Point 3 becomes the point of application of the resultant of $G_{c.m}$, ΣR_{xz}, ΣR_d, F_{fr}, $\Sigma R_{d.b}$, and Rr. This resultant is in equilibrium with the combined machine's traction force, P_{tr}, which passes through point 3 and the instantaneous center of rotation of the combined machine. Thus, the direction of the combined machine's traction force is determined by connecting point 3 and the instantaneous rotation center (marked "π" in the figure), i.e., direction ($3–\pi$).

To find the magnitude of the traction force, one draws from the endpoint of R_2 in the force polygon a line parallel to the support-wheel reaction ΣR_{wxz}, and from the polygon's origin a line parallel to the direction of the traction force. The intersection of these lines (in the force polygon) makes it possible according to the chosen scale to determine the magnitudes of the traction force and the support-wheel reaction.

Using this force polygon, the magnitude of the support-wheel reaction and the resultant of all resistance forces acting on the combined machine (equivalent to the traction resistance) were determined, and it totaled 32.3kN.

Next, the technical-operational indicators of the technological processes carried out by the combined machine (and also individually by the frontal plough, disc harrow, and roller) were calculated. These results are given in Table 1.

Comparative analysis of the technical-operational indicators of the proposed combined frontal plough and the individual operations (frontal plough, disc harrow, and roller independently) shows that, when using the proposed machine, the fuel consumption per hectare decreases by 3.83 liters or 8.9%, while the specific traction resistance (when the moldboard skimmers remain in the frontal plough's construction) is only 0.7kN higher than the sum of performing the individual technological operations separately. If the moldboard skimmers are removed (the proposed version), the specific traction resistance of the combined machine decreases by 1.91kN or by 11%.

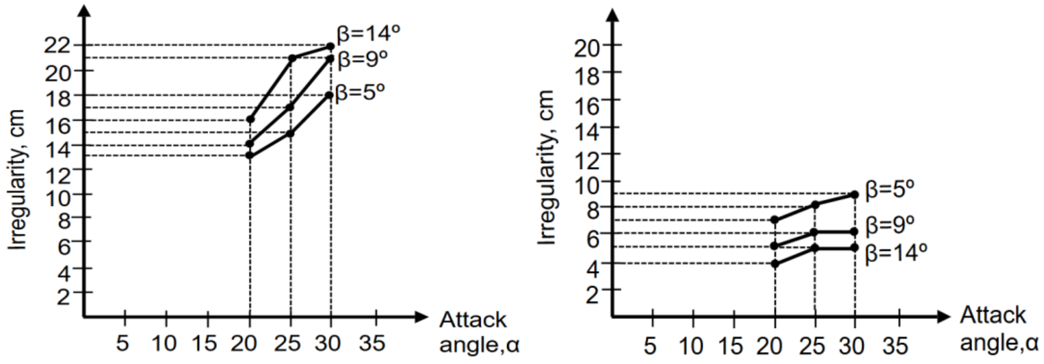
Table1.Results of calculating combined machine's technical, economic, energy indicator

Tractor	Farm Implements	Operating Speed (km/h)	Time Utilization Factor	Working Width (m)	Productivity (ha/h)	Fuel Consumption (l/ha)	Traction Resistance (kN)	Specific Traction Resistance (kN/m)
In the case of the combined machine								
T-150k	PFN-2A Frontal Plough without Moldboard Skimmers + Disc Harrow + Roller	5.2	0.85	2.1	0.928	38.9	32.3	15.3
In the case of separate technological processes								
T-150K	PFN-2A Frontal Plough with Moldboard Skimmers	5.5	0,89	2,1	1,03	31,5	30.57	14.56
MTZ-80.01	BDN-3 Disc Harrow	8	0,91	2,8	2,07	7.56	5.6	2,05
MTZ-80.01	3KKS-6 Roller	7.8	0,92	5,7	4,09	3,67	3.42	0.6
	Total							17,.21

If we also consider that the number of passes will be reduced by two thereby decreasing the machine-induced degradation of the soil (which will naturally have a positive effect on crop yields) it is clear that reducing the number of passes will likewise reduce wind erosion and certain operational costs. Hence, it becomes evident that the introduction and use of the proposed technology and technical equipment are efficient, economically feasible, and environmentally sustainable, making them a practical solution for modern agricultural practices. To analyze the technological indicators of the proposed combined machine's operation on slopes, the quality of cultivation was evaluated in field experiments under different disc attack angles and slope inclinations [OST, 2003. 16]. The purpose of this experiment is to assess the quality of the disc unit's work, improved by laboratory and field experiments, under mountain conditions. The slope inclination and the average disc attack angle were taken as independent factors, while the cultivation quality measured by the unevenness of the cultivated soilserved as the factor to be optimized. The goal of the experiment is to refine the disc attack angle for both uphill and downhill leveling on sloping ground. The object of the experiment is a pair of disc batteries set at different attack angles, determined in laboratory experiments. The experiment was carried out on three slope inclinations: 5°, 9°, and 14°. The individual disc attack angles of the disc batteries were chosen from three different ranges observed during laboratory experiments, for each slope inclination. The results are summarized in Table 2 and presented graphically in Figures 3 and 4.

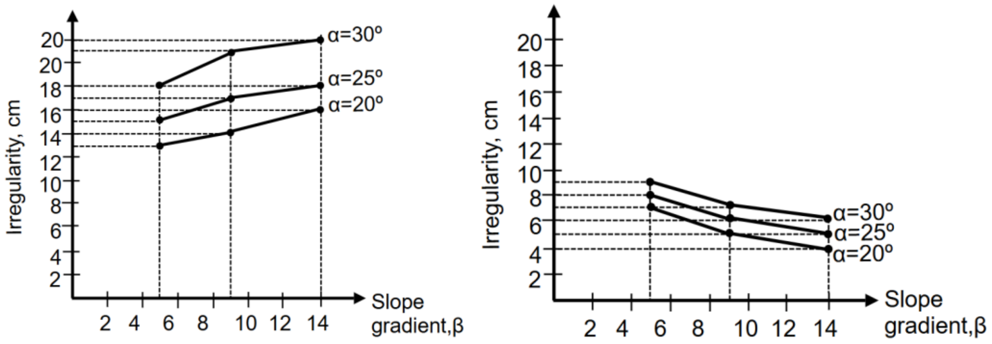
Table 2. Results of the experiments on the combined machine's disc unit

Experiment variant	**Disc attack angles (N1, N2, N3)**	**Measured Unevenness, cm**					
		Slope gradient 5^0		Slope gradient 9^0		Slope gradient 14^0	
		Uphill	Downhill	Uphill	Downhill	Uphill	Downhill
1	30^0,20^0,10^0 medium 20^0	13	7	14	5	16	4
2	35^0,25^0,15^0 Medium 25^0	15	8	17	6	18	5
3	40^0,30^0,10^0 Medium 30^0	18	9	21	6	22	5



A B

Figure 3. Variation of soil unevenness with disc attack angle for different slope inclinations: A. Uphill operation, B. Downhill operation



A B

Figure 4. Variation of soil unevenness with slope inclination for different disc attack angles: A. Uphill operation, B. Downhill operation

Analysis of the results of the field experiments shows that increasing the disc attack angle on slopes has a negative impact on the quality of soil cultivation when operating uphill, whereas operating downhill is not significantly affected. As the slope inclination increases, the quality of cultivation decreases, which is especially pronounced when working the soil uphill. When working downhill, the slope increase inclination reduce unevenness.

Conclusions

1. The proposed combined machine for soil cultivation is a complex mechanism consisting of multiple units, which has complicated its equilibrium problem. This problem was solved by a graphical method, also taking into account the results of theoretical research. Solving the equilibrium problem made it possible to assess the machine's energy indicators to outline ways to optimize these indicators, enhance the machine's structural reliability, reduce operational costs, and increase its overall economic efficiency**.**
2. Analysis of the technical-operational indicators of the combined machine showed that its use is expedient both from an economic point of view due to improved operational indicators and from an environmental point of view due to fewer passes in the field and reduced negative impact of the machinery.
3. Analysis of the field experiment results of the combined machine's disc batteries on slopes showed that increasing the disc attack angle when soil is being transported uphill adversely affects the quality of cultivation, whereas in downhill operation it has a positive effect. Therefore, based on the experimental results, the optimal disc attack angles were determined primarily by the data obtained for the uphill soil transportation scenario.

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Evaluation of technical-economic and technological indicators of the combined frontal plough for smooth plowing

Key words: combined machine, plow balance, disc, angle of attack, traction force, economic efficiency, fuel consumption, resistance, Roller

A technological scheme of the combined machine was developed, allowing for the determination of the coordinates of the point of application of the machine’s total weight force. Based on the results of theoretical research**,** the equilibrium problem of the proposed combined machine for soil cultivation was solved using a graphical method**,** and its energy performance was assessed. The technical-economic and operational indicators of the combined machine were determined, and through comparative analysis with base machines, the feasibility and efficiency of using the proposed machine were substantiated from both technological and economic perspectives**.**

Based on the results of experiments, the technological indicators of the disc working elements of the combined machine were analyzed during operation on slopes.

The research results provide an opportunity to outline the main directions for optimizing the parameters of the proposed combined machine and improving its design.