Theoretical Study of the Trajectory of Movement of a Ploughing Aggregate with a Reversible Plough on the Headlands

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Abstract Ploughing with reversible ploughs is increasingly used. Their main advantage is that the aggregates based on them allow ploughing without formation of dump ridges and breakup furrows (i.e. ensure formation of a smooth field surface). The trajectory of the movement of the ploughing aggregate with a reversible plough on the headlands has its own specifics and length due to the fact that the aggregate moves across the field in a shuttle way (i.e., processing is constantly carried out at the butt in relation to the previous pass). This trajectory depends on the length of the cultivated field and the working width of the plough. In comparison with the conventional aggregates the total length of the path of movement of the ploughing aggregates with reversible ploughs on the headland under certain conditions may be much larger. As estimated indicators in the work there are taken the total lengths of the trajectories of movement of the ploughing aggregates with reversible and conventional ploughs on the headland. On the basis of theoretical studies comparative calculated graphic

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dependences of the length of the trajectory of the movement of the ploughing aggregates were constructed for various lengths of the track (length of the cultivated field) and various plough widths. It will be an obvious advantage of the ploughing aggregate as part of a wheeled tractor with a minimum turning radius of not more than 5.3 m with a field length of 1400 m.

Keywords Turn · Headland · Ploughing width · Length of the field · Shuttle-like movement

1 Introduction

Reversible ploughs of various designs are widely used in the world [1–4].

The developers of these machines, together with the researchers, pay great attention to the improvement of the plough bodies and other elements [5–8]. In agrotechnical terms, they are interested to improve the running stability and performance quality of reversible ploughs both in a horizontal and a longitudinal-vertical plane [9, 10].

It should be noted that during the main operations the mode and trajectory of movement of the ploughing aggregates with reversible and conventional ploughs have no fundamental difference. This difference manifests itself when running of these ploughing aggregates on the headland.

The main advantage of the reversible ploughs is their ability to perform ploughing without tailing ridges and back furrows (Fig. 1) [11]. In this case the machine-and-tractor aggregate moves in a shuttle-like manner. In the process of moving on the headland, it makes loopy and, as a rule, pear-shaped turns. But the execution of such a maneuver is more complicated than, for instance, a loopless turn. And this complexity is the higher, the smaller is the width of the ploughing aggregate [12, 13].

When ploughing with a conventional plough, the ploughing aggregate with a working width B_p also performs loopy pear-shaped turns. But it does this only at the initial stage of work. And this stage continues until, after n passes of the aggregate, the width of the ploughed area (S_p) becomes equal to, or greater than twice, the minimum turning radius (R_o) of the tractor [14]: $S_p = n \cdot B_p \geq 2\,R_o$. After that such a ploughing aggregate makes ordinary loopless turns with a rectilinear section.

As a result, it may turn out that, under certain conditions of work on the headlands of the field, the total length of the path of movement of the ploughing aggregates with reversible and conventional ploughs will be different. Because of this, the time spent by them for non-useful work will also be different. An aggregate with a large value of such time will have a lower performance and worse indicators of the specific fuel consumption. A priori assuming an increase in the non-productive time, spent by the ploughing aggregate with a reversible plough, the researchers propose certain solutions to this problem. One of them is the equipment of the ploughing aggregate with a reversible plough of special navigation systems [15]. Another solution is to

Fig. 1 Ploughing with a reversible plough

complicate the design of the tractor itself [16, 17]. It is a special device in the form of an additional support wheel which, after the unit has entered the headland, raises the front steering wheels of the tractor. As a result, turning of the aggregate takes place relative to the support point of the left or right rear wheel of the tractor that is braked during the turn. According to research data such a change in the design of the tractor reduces the width of the turning lane of the aggregate by 50%. In addition, the reduction in turning time reaches 35%. It should be emphasized that in practice the arable plots quite often have a shape that differs to varying degrees from the rectangular one. The choice of the optimal trajectory for turning the ploughing aggregate with a reversible plough, when working under such conditions, is a subject of research [18–22].

However, the authors of this article did not find studies that would allow giving a comparative assessment of the modes of movement of the ploughing aggregate on the headland, based on a reversible and a simple plough. Moreover, there are practically no such data for individual ploughing aggregate, gained on the basis either of a reverse plough or a conventional plough. As a result, this state of affairs does not allow one to decide more or less unequivocally on the expediency of using a reversible plough instead of a conventional one. In view of the foregoing, the present article is devoted to solving this problem)”.

2 Materials and Methods

As indicators for estimation here were selected the total lengths of the trajectories (paths) of movement the ploughing aggregates with reversible ($\sum L_{xp}$) and conventional ($\sum L_{xs}$) ploughs on the headland.

For their calculation, we used our previously obtained theoretical assumptions (Bulgakov et al., 2016):

$$\sum L_{xp} = (7R_o + 2E) \cdot \left[Integer\left(\frac{\sqrt{2 \cdot \left(8R_o^2 + B_p L_p\right)}}{B_p} \right) - 1 \right] \quad (1)$$

$$\sum L_{xs} = (7R_o + 2E) \cdot \left[Integer\left(\frac{2R_o}{B_p} \right) - 1 \right] + (1.7R_o + 2E) \cdot \left[Integer\left(\frac{\sqrt{2 \cdot \left(8R_o^2 + B_p L_p\right)}}{B_p} \right) - Integer\left(\frac{2R_o}{B_p} \right) \right] + B_p \sum_{i=0}^{n_{bp}} i \quad (2)$$

where E – the path of movement of the ploughing aggregate on the headland before it begins to turn, m; L_p – the length of the arable area of the field, m; n_{bp} − the number of the loopless turns, performed by the ploughing aggregate with a conventional plough. Their number is determined from the following equation:

$$n_{bp} = Integer\left(\frac{\sqrt{2 \cdot \left(8R_o^2 + B_p L_p\right)}}{B_p} \right) - Integer\left(\frac{2R_o}{B_p} \right) \quad (3)$$

The designations of the remaining parameters, included in Eqs. (1)–(3), are indicated above in the text of the article.

In the research there were evaluated ploughing aggregates the ploughs of which are equipped with 0.35 m wide bodies. The smallest working width of the compared ploughing aggregates $B_p = 1.75$ m, and the largest - $B_p = 3.15$ m. These values correspond to the plough designs with 5 and 9 bodies, respectively.

A tractor was selected as the base one the minimum turning radius of which was changed within a 4–7 m range. The following values of parameter E corresponded to the ploughing aggregates composed on the basis of such a tractor were: 8.5; 9.5; 10.5; 11.5; 12.5 m.

The value of the length of the arable plot in the theoretical calculations was changed within a range $L_p = 600–1400$ m.

3 Results and Discussion

Dependences (1) and (2) were obtained by comparing the operation of the ploughing aggregates with reversible and conventional ploughs on an arable plot of optimal width (C_{opt}, m). The value of this indicator is determined from the following relationship [23, 24]:

$$C_{opt} = \sqrt{2 \cdot \left(8R_o^2 + B_p L_p\right)} \tag{4}$$

The results of calculations using dependencies (1) and (2) show that, when the operating width B_p of the compared ploughs changes from 1.75 to 3.15 m, the values of the optimal width of the arable plots C_{opt} change from 50 to about 95 m (Fig. 2).

The smallest range of variation of this parameter (from 50 to 63 m) occurs at the field length $L_p = 600$ m (the red line 1, Fig. 2) but the largest (from 72 to 93 m) at $L_p = 1400$ m (red line 3). This fact indicates that the intensity of growth of the optimal width of the arable land is directly dependent on the increase in the length of the field. This fact indicates that the intensity of the growth of the optimal width of the arable land is directly dependent on the increase in the length of the field.

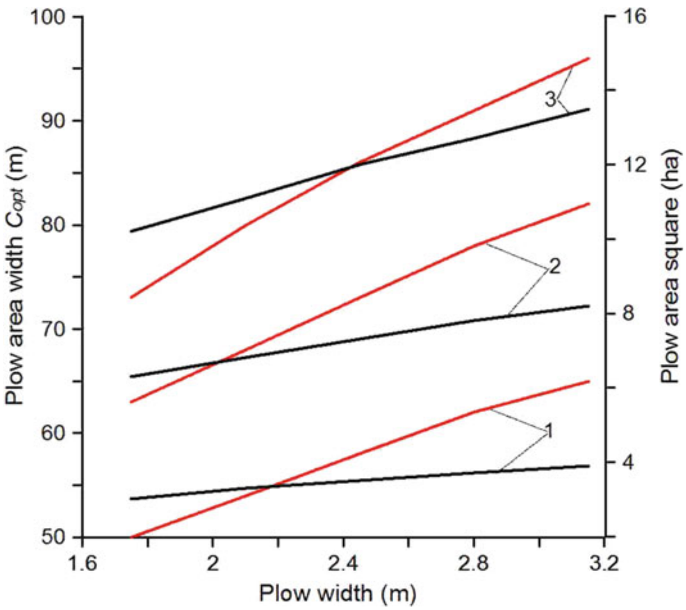

Fig. 2 Dependence of the optimal width of the arable plot (—) and its area (—) upon the operating width of the plough for various lengths of the field: 1 − $L_p = 600$ m; 2 − $L_p = 1000$ m; 3 − $L_p = 1400$ m

A quantitatively different but qualitatively similar nature of the change corresponds to the dynamics of the growth of the arable land area as parameters B_p and L_p increase (the black lines, Fig. 2).

When processing plots with such optimal values of the width and area, it turned out that expedience of using a ploughing aggregate with a reversible plough depends significantly on the length of the field. With the value of this parameter at the level of 600 m, the path travelled by the ploughing aggregate with a reversible plow on the headland for all values of the machine-tractor unit operating width is greater (curves 1, Fig. 3).The equality of the values of the indicators ΣL_{xp} (the reversible plough) and ΣL_{xs} (the ordinary plough) takes place at point *A*. This corresponds to the maximum value of parameter $B_p = 3.15$ m. At the minimum value of parameter $B_p = 1.75$ m indicator ΣL_{sp} is by 13% higher than the similar indicator ΣL_{xs}.

Analysis of these results leads to the conclusion that, when the length of the working area of the cultivated field is 600 m, the use of the ploughing aggregate with a reversible plow is not expedient.

When the field length is 1000 m and the plough working width is 1.75 m, the conventional ploughing aggregate has again an advantage, though a minimal one. The equality of the values of indicators ΣL_{xp} and ΣL_{xs} occurs at point *B* (Curves 2, Fig. 3), which corresponds to the plough width of 1.9 m. With a further increase in the value of this design parameter, the advantage passes to the ploughing aggregate with a reversible plough. At $B_p = 3.15$ m indicator ΣL_{xp} becomes less by 13% than the similar indicator ΣL_{xs}.

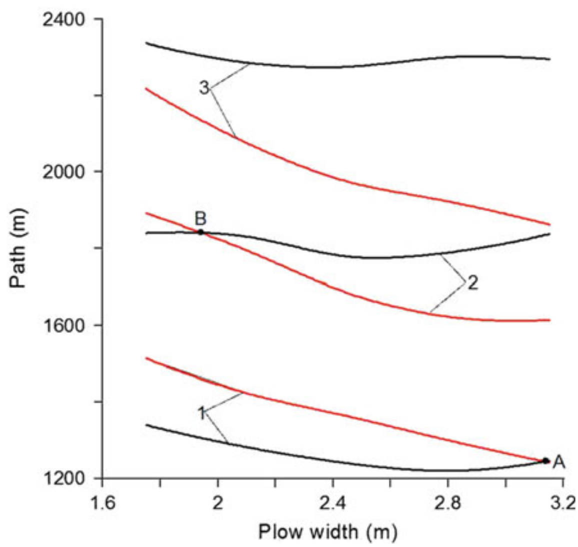

Fig. 3 The path of movement of the ploughing aggregate with a reversible (—) and a conventional (—) plough on the headland upon the width of the plough at different values of the length of the field: $1 - L_p = 600$ m; $2 - L_p = 1000$ m; $3 - L_p = 1400$ m

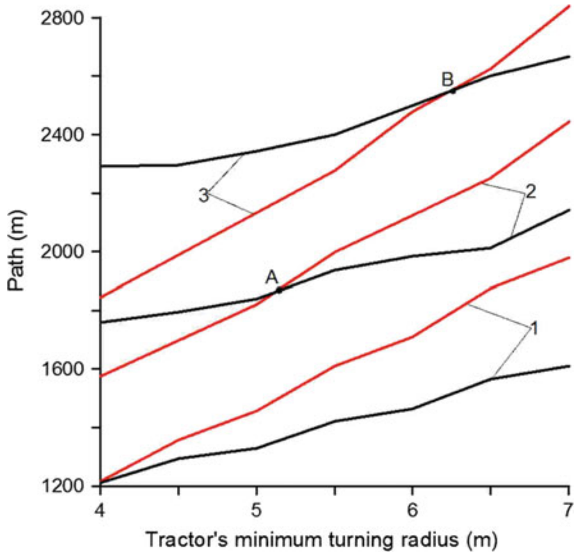

Fig. 4 The path of movement of the ploughing aggregate with a reversible (—) and a conventional (—) plough on the headland upon the minimum turning radius of the tractor at various values of field length: 1 – $L_p = 600$ m; 2 – $L_p = 1000$ m; 3 – $L_p = 1400$ m

The ploughing aggregate with a reversible plough gains full advantage when working on a field the length of which is 1400 m (Curves 3, Fig. 3). In this case the decrease in indicator ΣL_{xp} as compared to the similar indicator ΣL_{xs} increases from 5% (at $B_p = 1.75$ m) to 20% (at $B_p = 3.15$ m).

When the length of the field is 600 m, the length of the trajectory of the aggregate with a reversible plough will be longer than usual for any value of the minimum turning radius (Curves 1, Fig. 4). When the length of the field is 1000 m, the situation depends on the value of parameter R_o. At $R_o \leq 5.3$ m, the aggregate with a reversible plow has the best performance. In this case the value of indicator ΣL_{xp} is less than the value of indicator ΣL_{xs} (Curves 2, Fig. 4). At point B, which corresponds to the value of parameter R_o approximately 5.3 m, the difference between the values of these indicators is equal to zero. With further increase in the minimum turning radius of the tractor (and in this case, of the entire aggregate), a ploughing aggregate with a conventional plough becomes more efficient. A qualitatively similar result takes place when the length of the arable field is 1400 m. The only difference is that the preference of the ploughing aggregate with the reversible plough is maintained when the value of parameter R_o is increased to about 6.6 m (Curves 3, Fig. 4). At $L_p = 1400$ m the efficiency of the ploughing aggregate with a reversible plough has the greatest value when parameter R_o has a minimum value, i.e., 4 m. In this case, the value of the estimation indicator ΣL_{xp} is by 20% less than the value of indicator ΣL_{xs}. It should be added to the above analysis that the practitioners are aware of the technological methods that allow the operation of the ploughing aggregate with a conventional plough virtually without any dump ridges and breakup furrows. One should not forget the fact that the ordinary plough is almost three times cheaper and much less complicated than the reverse one. All this indicates that without justified analysis the use of the latter may not be economically profitable. That is why the above research results may be useful when substantiating the choice of the type of the plough.

4 Conclusions

From the point of view of the length of the trajectory of movement the expediency of using a ploughing aggregate with the reversible plough essentially depends on the length of the field and the working width of the aggregate. With the value of this parameter at the level of 600 m, the use of a ploughing aggregate with the reversible plough instead of the usual one is characterised by an increase in the total path of its movement on the headland. When the working width of the aggregate is increased from 1.75 to 3.15 m, this growth takes place at any (from those considered in the calculations) minimum turning radius of the tractor, and it reaches 13%.

When the length of the field is 1000 m, the advantage of the ploughing aggregate with a reversible plough over the conventional one takes place at a working width of more than 1.9 m, and with a minimum tractor turning radius of less than 5.3 m.

Full advantage of the ploughing aggregate as part of a wheeled tractor with a minimum turning radius of not more than 6.3 m and a reversible plough takes place at the length of the field 1400 m. In comparison with the usual one, the total path of movement of such an aggregate on the headland, depending on its working width, is reduced by 5–20%.

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