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Experimental investigation of the work of a ploughing aggregate, operating according to the system 'push-pull'

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Abstract. The use of ploughing machine-and-tractor aggregates, operating according to the principle of 'push-pull', finds increasing application in the world since it allows ensuring the stability of the movement and the depth of ploughing, reduction of the energy indicators. The aim of this experimental study is to determine under field conditions the dynamic and operational technological parameters of the ploughing machine-and-tractor aggregate, operating according to the 'push-pull' system. This aggregate was an integral ploughing-tillage wheeled HTZ 16131 tractor, in front of which there was mounted a two-bottom plough, and at the rear – four-bottom ploughs. This aggregate has satisfactory path parameters of the movement during the execution of the technological process of ploughing. The oscillations of the furrow path for this aggregate are of a low-frequency nature and are concentrated in a rather narrow frequency range (0...50 m^{-1}). At the operating speed of 2.0 $m \cdot s^{-1}$ it is 0...0.16 Hz. The maximum value of the mutual correlation function between the input impact (the turning angle of the driven wheels of the aggregating tractor) and the output value – its relative bearing is positive and reaches a value of 0.88. Stability of the ploughing depth for the aggregate according to the '2 + 4' scheme is ± 1.65 cm^2, which is normally the smaller value of the same indicator for a serial ploughing aggregate (± 1.98 cm^2).

Keywords: ploughing, aggregate, system 'push-pull', indicators.

INTRODUCTION

One of the most important tasks of agricultural production is to reduce the energy costs of ploughing (Barwicki et al., 2012; Valainis et al., 2014). An important point in solving this problem is to increase the tractive-coupling properties of the aggregating tractor by increasing its coupling weight (Bulgakov et al., 2016).

As part of a ploughing machine-and-tractor aggregate, this can be achieved by using ploughs attached to the aggregating tractor according to the scheme ‘push-pull’ (Rucins & Vilde, 2005). As investigations show, due to the vertical component of the draught resistance of the frontal plough, additional load of the frontal wheels increases, and, consequently, the coupling weight of the tractor increases. As a result, this leads to a certain reduction in slipping and lower fuel consumption by the ploughing aggregate (Nadykto et al., 2017).

However, if the frontal plough is not correctly connected to the source of power, not additional loading of the frontal wheels of the aggregating tractor may occur, but vice versa – their insufficient loading with inevitable loss of the steering ability and stability of the movement of the entire ploughing machine-and-tractor aggregate (Bulgakov et al., 2017).

In order to meet agrotechnical requirements for the quality of ploughing during the study of the operation of the frontal plough as part of the ploughing aggregate, operating according to the push-pull scheme on the basis of a modular source of power tool MEZ-200 (Bulgakov, 2008, Bulgakov et al., 2015), it was suggested to locate the support wheel of the frontal plough outside the furrow, i. e., on the untilled field at the same time, the removal of the said wheel from the furrow generates a stability problem of the movement of the frontally mounted ploughing tool in a horizontal plane when it is pivotally attached to the source of power. Without a support the frontal plough may take the extreme (left or right) deviated position, and not leave it afterwards. It is quite clear that further work of such a ploughing machine-and-tractor aggregate will be practically impossible.

An important point in assembling a ploughing machine-and-tractor aggregate, operating according to the ‘push-pull’ scheme, is to determine the ratio between the number of bodies of the frontal and the rear-mounted ploughs. The least common option is ratio 1:1. It has been established by investigations of the previous years (Köller, 1983) that the front-mounted plough should have fewer bodies than the rear plough. Usually the smallest number of bodies of a frontal ploughing tool is two. No less common variant in the world, operating according to the ‘push-pull’ scheme, is application of a three-furrow ploughing frontal tool.

In selecting a ratio between the number of the frontal and the rear plough bodies, a fact is taken into account that stability in a horizontal plane of the movement of an aggregate operating according to the ‘2 + 4’ scheme can be higher than that of the aggregates assembled according to the schemes ‘2 + 3’ or ‘3 + 4’ (Kasymov, 1988). The authors of this same work believe that for better steering ability of the movement, the draught resistance of the front-mounted plough should not exceed 40% of the total draught resistance of the entire ploughing machine-and-tractor aggregate.

At the same time, according to various publications, the highest increase in the efficiency of ploughing is achieved by ploughing aggregates, assembled according to the ‘3 + 4’ and ‘3 + 5’ schemes. The increase in this indicator reaches 58...60% (Köller, 1983). In this case somewhat doubtful is the 57% reduction in the specific fuel consumption by the aggregate, assembled according to ‘2 + 3’ scheme.

Our theoretical studies have established that, in order to avoid insufficient loading (underloading), and, vice versa, – unloading of the frontal wheels of the tractor with a nominal tractive effort of 30...32 kN, the frontal plough should have two bodies, and the rear plough should have 4 bodies (the ‘2 + 4’ assembling scheme) (Kistechok, 2016). The aggregating wheeled tractor moving with the right-side wheels along the furrow with the frontal plough being rigidly attached to it in a horizontal plane and the supporting wheel of this plough located outside the furrow.

The aim of the research is to carry out under field conditions experimental evaluation of the draught-and-power indicators and agrotechnical indicators of the operation of a ploughing aggregate, operating according to the 'push-pull' scheme with the number of plough bodies '2 + 4'.

MATERIALS AND METHODS

The ploughing machine-and-tractor aggregate, studied by us, was assembled according to the 'push-pull' scheme and consisted of a HTZ 16131 tractor with engine power 132 kW (category III of the tractor power in accordance with ISO 730/1 and 730/3-82), a frontal two-furrow plough (of our design), and a rear-mounted tensometric plough (Fig. 1). As it was mentioned above, in order to avoid a case of underloading, and, vice versa, – unloading the frontal wheels of the said wheeled aggregating tractor, the rear plough must have 4 bodies. For this purpose, in the process of experimental field investigations with a five-furrow tensometric plough, one body was removed. In this way an experimental ploughing aggregate was assembled according to the '2 + 4' scheme, which had a frontal two-furrow and a rear-mounted four-furrow plough.

The following parameters were recorded during the tests: humidity and density of the soil, the longitudinal-vertical profile of the field, the draught resistance and the working width of the ploughs, the speed of the movement, skidding of the wheels and the hourly fuel consumption by the tractor, as well as the depth of ploughing.

Figure 1. A ploughing aggregate, assembled according to the 'push-pull' scheme.

The physical characteristics of soil were determined by the methodology described in (Arshad et al., 1996; Standard 5180-2015, 2016). The moisture content of soil, according to this methodology, was determined using a drying chamber.

The density of soil was determined by a specially made densitometer in the form of a metallic cylindrical beaker. In this case we were guided by the following procedure (Dospehov, 1985; Tamm et al., 2016).

The depth of ploughing by the aggregate was measured during the research process by a developed depth gauge. The number of measurements was 50, and the measurement pitch (interval) was 0.5 m.

For the characteristics of the agrotechnical background, the required number of sampling replications (n) was determined from the known expression (Nalimov & Chernova, 1975):

$$n = Intg\left(\frac{tV}{\rho}\right)^2 \quad (1)$$

where t – a normalised value of Student's t-criterion at a confidence level of 95% (t = 1.96); V, ρ, – the coefficient of variation and the allowed deviation (the accuracy factor) of the measured parameter.

It is known that for most technical problems it is not necessary to determine the measurement error with accuracy greater than 10% (Venikov, 1986). Proceeding from this, we assumed in the calculations that $\rho = 0.1$.

It has been established by many years' experiemnts that the variation coefficient of the soil humidity and density usually does not exceed 10%, that is, the variability of these parameters is low. In this connection we assumed that $V = 0.1$. Uneven soil contamination is usually higher, therefore, taking into account the results of previous measurements, the variation coefficient for this process, was assumed to be equal to $V = 0.2$. As a result, we obtained the following replication rates for the experiments: when measuring the soil humidity and density, n = 4; when determining the field contamination, n = 16.

The experimental studies were conducted on a field with the following characteristics: the type of the soil – dark chestnut; the relief – flat; the microrelief – levelled; the agrotechnical background – a disked sunflower stubble; the soil humidity in a layer of 0...30 cm – 13...14%; the soil bulk density in a layer of 0...30 cm – 1.26...1.29 $g \cdot cm^{-3}$; the humus content – 4.7%, the soil weediness – 95 $pcs \cdot m^{-2}$.

Taking into account the design features of the investigated ploughing machine-and-tractor aggregate to carry out its experimental studies, we developed a complex of measuring and recording equipment, which allowed obtaining unbiased evaluation of the investigated parameters (Fig. 2).

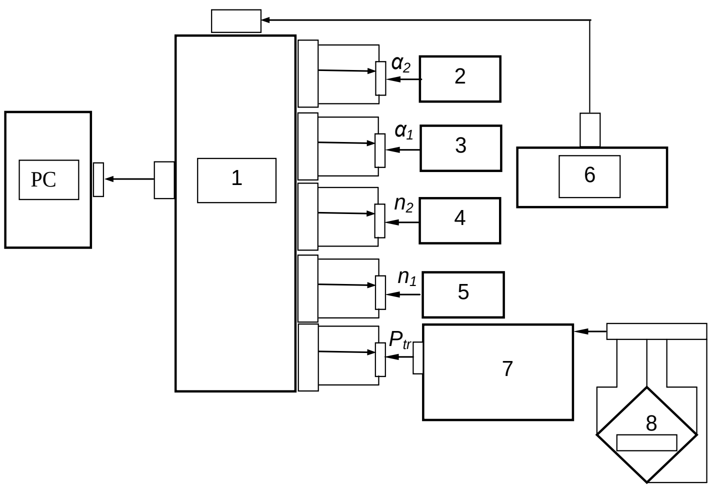

Figure 2. S block diagram of the measuring and recording complex: PC – a computer; 1 – an analogue-to-digital converter; 2, 4, 5 – current collectors; 3 – variable resistance; 6 – a power supply unit; 7 – a kb-8 balancing box; 8 – a tensometric bridge; α_1 – the turning angle of the lower links of the tractor rear linkage; α_2 – the relative bearing of the tractor; n_1 – revolutions of the right-side frontal wheel of the tractor; n_2 – revolutions of the track measuring wheel; p_{tr} – the draught resistance of the rear-mounted plough.

During the experimental field studies of the ploughing aggregate the following data were synchronically transferred to the analogue-to-digital convert and recorded (Fig. 2): the draught resistance of the rear-mounted plough; revolutions of the tractor wheels; revolutions of the track measuring wheel; the relative bearing of the tractor; the turning angle of the lower links of the HTZ 16131 tractor rear linkage in a horizontal plane; the tractor.

The moisture content of the soil was determined by the conventional hot drying method. To measure the agrotechnical background density, a method and instrument specially developed by the authors were used (Nadykto, 2017). The amplitude fluctuations and the frequency of the field profile irregularities in a longitudinal direction were measured with the help of a special profilograph (Fig. 3) according to the procedure described in (Kuvachov, 2008).

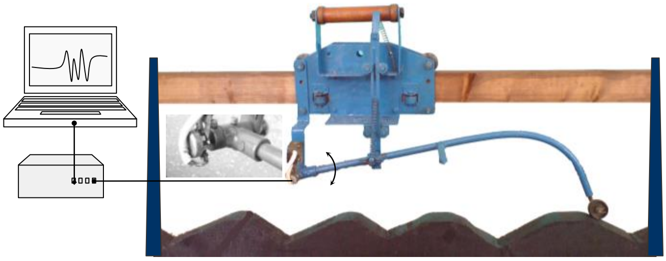

Figure 3. A scheme of the measuring equipment for profiling the irregularities of the agricultural background (agrophone).

The draught resistance of the ploughs was measured and then recorded using a tensometric link designed for a tractive effort up to 40 kN. In order to measure the draught resistance of the rear-mounted plough, the latter was equipped with a frame pivotally attached to it. With its front part this frame was connected to the rear linkage attachment of the tractor HTZ 16131, but with its rear part – through the measuring element – to the frame of the plough. The speed of the working movement of the ploughing aggregate was fixed by means of a track measuring wheel installed on the tractor. On the hubs of its frontal and rear axles, counters of revolutions were installed the electric signals of which were taken by means of current collectors.

Two impulse-type flowmeters IP-151 were used to measure the hourly fuel consumption of the investigated aggregating tractor. One of them fixed the supply of fuel to the fuel pump of the tractor, and the other – the amount of fuel returned to the fuel tank. Electrical signals processed by a profilograph, the tensometric unit, the track measuring wheel, the revolution counters and the fuel meter were recorded on the PC, passing them through an analogue-to-digital converter. Repeatability of the measurements of all the parameters was 5.

The frontal plough and the rear-mounted plough of this ploughing machine-and-tractor aggregate were adjusted for a 25 cm depth of ploughing. The operational and technological parameters of the explored ploughing machine-and-tractor aggregate, assembled according to the ‘push-pull’ scheme, were calculated using a methodology laid out in standard (Standard 24055-2016, 2016) and specially developed software.

RESULTS AND DISCUSSION

As a result of investigations, it was found out that fluctuation in the field profile irregularities were of a high-frequency nature. This fact is unambiguously shown by the length of the correlation link of the ordinates of this process, which was less than 0.3 m. The normalised correlation function of the field surface profile fluctuations included a certain periodic component with a period of approximately 0.75 m. The dispersion of the fluctuations was also small (1.21 cm^2) and was concentrated in the frequency range of 0...12 m^{-1}.

At a speed of the ploughing aggregate 1.98 m s^{-1} this is 0…24 s^{-1} or 0...4 Hz (Fig. 4). It follows from this that a relatively high frequency and a small dispersion of the irregularities of the longitudinal-vertical field profile can be generators of more or less significant fluctuations of the draught resistance of the frontal and the rear-mounted plough. The basic trend of this parameter (i.e., the draught resistance) should be formed by the internal structure of the soil environment with which the operating surfaces of the ploughing tools are in contact.

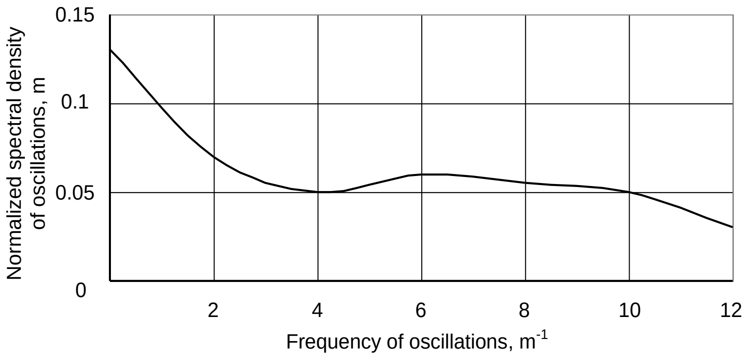

Figure 4. A normalised spectral density of the field profile fluctuations.

For the rear-mounted plough the draught resistance varied within the limits of 21.0...23.1 kN. The draught resistance of a double-furrow frontal implement was 10.5...11.6 kN. The total resistance of both ploughs was 31.5...34.7 kN. With this in mind, we can say that with an average quadratic deviation of ± 5.0 kN, the variability of the draught resistance of the entire ploughing aggregate according to the 'push-pull' scheme was average since the coefficient of variation of this process was within the range of 14...16%. Analysis of the normalised correlation functions of the draught resistance of ploughs showed that the time of the correlation link was within 0.24...0.26 s. Such duration (in time) of the correlation link characterises the process as a relatively high-frequency one. The real proof of this is the dispersion spectrum of the fluctuations in the draught resistance of the investigated ploughing aggregate, concentrated within the frequency range of 0...25 s^{-1} or 0...4 Hz (Fig. 5).

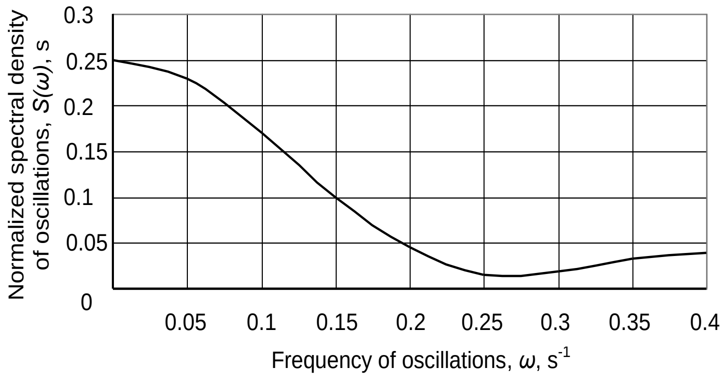

Figure 5. Normalised spectral densities of fluctuations in the draught resistance of a rear-mounted plough within the ploughing machine-and-tractor aggregate assembled according to the scheme 'push-pull'.

The results of the experimental field research of the ploughing machine-and-tractor aggregate, operating according to the 'push-pull' scheme, are presented in Table 1. Because of the frontal plough, additional loading of the frontal wheels of the investigated tractor, and, consequently, its coupling weight increased, which allowed it to aggregate a total of 6 bodies of the plough, in contrast to the basic version of the ploughing aggregate, based on it, aggregated only with the rear-mounted five-furrow plough. This provided a possibility to increase the actual working width of the ploughing aggregate, assembled according to the 'push-pull' scheme, by 20.9% (Table 1). As a result, the efficiency of the investigated aggregate per hour of the basic time turned out to be by 19.5% higher than that of the ploughing aggregate with a rear-mounted 5-furrow plough.

Table 1. The results of the experimental research of the ploughing aggregate, operating according to the scheme 'push-pull'

Composition of the ploughing aggregate, assembled according to the 'push-pull' scheme	Operating speed, $m \cdot s^{-1}$	Operating width, m	Efficiency per 1 hr of the basic time, $ha \cdot hr^{-1}$	Depth of ploughing, cm	Skid-ding of the wheels of the tractor, %	Draught resistance of the plough, kN	Hourly fuel consumption, $kg \cdot h^{-1}$	Specific fuel consumption, $kg \cdot ha^{-1}$
HTZ 16131 + frontal two-furrow plough + a rear- mounted four-furrow plough	1.98	2.14	1.53	25.1 ± 0.1	14.4	33.1	22.3	14.6

It is known that one of the main agrotechnical indicators of the operation of a ploughing aggregate is the uniformity of the tillage depth. According to the experimental data, the mean square deviation of the ploughing depth and working with a 'push-pull' aggregate did not exceed agrotechnical requirements (± 2 cm) and amounted to ± 1.52 cm. In addition, higher stability in the tillage depth was observed. One of the reasons for the implementation of the ploughing process with a higher stability of the tillage depth may be a circumstance that the front axle of the tractor HTZ 16131, having a frontal implement, produces lesser vertical vibrations when moving along the furrow. In general, this is positively reflected in the smoothness of the movement of both the frontal and the rear-mounted ploughs.

Analysis of the normalised correlation function and the spectral density of the fluctuations of the ploughing depth of the ploughing aggregate assembled according to the ‘push-pull’ scheme showed that the length of the correlation link is at least 21 m. The main share of dispersion of the ploughing depth of the tested ploughing aggregate is concentrated within a rather narrow frequency range: 0...0.45 m^{-1}. When the speed of the forward movement of the ploughing aggregate is at the level of 2.0 $m \cdot s^{-1}$, this is 0...0.90 s^{-1}, or only 0...0.14 Hz. The fluctuations in the ploughing depth themselves do not contain any latent periodic component. And this, despite the fact that the correlation function of the field profile fluctuations includes such a component with a period of approximately 0.75 m. The manifestation of the latter phenomenon can be explained by the fact that the basic soil tillage was carried out across the rows of the harvested sunflower, sown with a row spacing of 0.7 m. In the process of its growing hilling of the sprouts was carried out, which caused the appearance of periodic hillocks on the field at a distance of about 0.7 m. The results of the operational and technological evaluation of a ploughing aggregate, operating according to the ‘push-pull’ scheme on the basis of the HTZ 16131 tractor, are presented in Table 2.

Table 2. The operational and technological evaluation of a ploughing aggregate, operating according to the ‘push-pull’ scheme on the basis of the HTZ 16131 tractor

Indicator	Value
Operating conditions:	
– working width, m	2.15
– operation travel speed, $km \cdot h^{-1}$	7.2
– installed depth of ploughing, cm	25
– length of the furrow, m	1,150
Amount of the performed work, ha	40
Efficiency of the work, $ha \cdot h^{-1}$:	
– basic time	1.55
– shift time	1.33
– operating time	1.30
Specific fuel consumption, $kg \cdot ha^{-1}$	14.4
Operational and technological coefficients:	
– the use of the shift time	0.86
– the use of the operating time	0.84
– reliability of the technological process	0.99
– the use of the operation travels	0.90
The average duration value of one ‘pear-shaped’ turn, s	53
Width of the turning strip, m	32.1
Agrotechnical indicators:	
– average value of the ploughing depth, cm	25.7
– uniformity of the ploughing depth, ±cm	1.65
– uniformity of the working width, ± cm	6.8
– gaps (stoppages)	none

Analysis of the data, obtained from testing the experimental ploughing aggregate (Table 2), in contrast to the serial ploughing aggregate, showed a 14.7% decrease in labour costs, direct costs by 17.0%, specific capital investments by 10.8%, and reduced costs by 15.8%, indicating undoubted advantages of the aggregates of the ‘push-pull’ system.

CONCLUSIONS

1. The conducted experimental field investigations show that the advantage of frontal aggregation of agricultural implements with a wheeled HTZ 16131 tractor, makes it possible to create on its basis highly efficient ploughing-machine-and-tractor aggregates operating according to the ‘push-pull’ scheme. The results of the experimental study provided a possibility to establish that the discrepancy between the theoretical and experimental amplitude-frequency characteristics of the movement is not more than 8%.

2. The ploughing aggregate of such a scheme, composed from the HTZ 16131 aggregating wheeled tractor, a double-furrow frontal and a four-furrow rear plough (‘2 + 4’ scheme), allows to increase the actual working width by 20.9%. As a result, the efficiency per hour of the basic time of the ploughing aggregate, combined according to the ‘push-pull’ scheme, was by 19.5% higher than the base machine-and-tractor aggregate with one rear-mounted 5-furrow plough. Due to the achieved higher efficiency of work, the specific metal content of the investigated ploughing aggregate was by 10.7% less.

3. The fluctuations of the furrow path for this aggregate are of a low-frequency nature and are concentrated in a rather narrow frequency range (0...50 m^{-1}). The operating speed of the movement being 2.0 $m \cdot s^{-1}$, this is 0...0.16 Hz. With an operating speed of 2.0 $m \cdot s^{-1}$ this is 0...0.16 Hz. The maximum value of the mutual correlation function between the input impact (the turning angle of the driven wheels of the aggregating tractor) and the output value – its relative bearing, is positive and reaches a value of 0.88.

4. The machine-and-tractor ploughing aggregate, working according to the ‘push-pull’ scheme, carries out the technological process of ploughing with a higher depth stability of processing. The average square deviation of the ploughing depth of the investigated aggregate is ± 1.52 cm and it is within the allowed agrotechnical limits. The ploughing depth stability of the aggregate, working according to the ‘2 + 4’ scheme, is ± 1.65 cm^2, which is naturally a smaller value of the same index for the serial ploughing aggregate (± 1.98 cm^2).

5. The comparative tests of this ploughing aggregate with the serial one allow reducing: labour costs by 14.7%, direct costs by 17.0%, specific capital investments by 10.8%, reduced costs by 15.8%.

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