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Development of Closed-Circuit Elastic Mounting for Working Bodies in the Interrow Cultivator

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Abstract

The main drawbacks of cultivators intended for the tillage of stony soils are low reliability of the working bodies, high draught resistance and inability to maintain the required depth of tillage. Hence, the scientists in the Gorsky State Agrarian University conducted a range of studies and trials that allowed them to improve the design. The aim of the present study was to develop a new design of the closed-circuit elastic suspension for the working bodies of a cultivator that is intended for the performance on stony soils and provides high reliability, low draught resistance of the working bodies (in comparison with the existing models), and the required depth of tillage. The tests of the proposed design were performed in the laboratory conditions on a specially designed and constructed stand equipped with tensometric devices. Horizontal and vertical stiffness of the suspension and its frequency was studied. The field trials were performed by a specially constructed machine that was mounted on a tractor. The machine was equipped with tensometric gauges that were reading the sensors with the frequency of 1000 times per second. All the primary data were processed by the respective methods of mathematical statistics. The authors identified the effective model of the closed-circuit elastic suspension for the central working body with the radius of bows R_1=125mm, R_2=135mm, horizontal stiffness C_{hor}=25.6 N/mm and natural vibration frequency $\nu \in [10.2…16.2]$ Hz. A closed-circuit bow type suspension with the stiffness C_{hor}=18.34 N/mm and natural vibration frequency $\nu \in [8.5…8.7]$ were most suitable for the side working bodies of a cultivator. It was established that in comparison with the traditional mounting of working bodies, the designed elastic suspension of the working bodies provided the reduction of the draught resistance by 3.7…15%, high reliability and uniform required depth of tillage.

Keywords: Elevated Water Tank; Soil-Structure Interaction; Fluid-Structure Interaction; Load Pattern; Incremental Dynamic Analysis (IDA); Pushover; Nonlinear Response History Analysis (NLRHA).

1. Introduction

Cultivators, special industrial machines, include two major groups: cultivators with firm mounting of the working bodies and cultivators with pivot mounting which design is based on a parallelogram suspension frame for the working bodies. The later have a complicated construction but proved to be efficient due to proper copying of the soil microrelief by the working sections. However, when such cultivators are used on stony soils, they often break down (the beams and uprights bend, etc.). Lately, there has been a tendency in agricultural machinery for mounting the interrow cultivators

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with an elastic suspension of the working bodies or elastic uprights, which allows for the improvement of the tillage quality and the reduction of draught resistance of the working bodies. However, these uprights and suspension have low stiffness and are not suitable for stony soils in submontane and mountainous zones of the Republic of North Ossetia–Alania.

According to the publications of the last three years, a significant contribution to the development of elastic uprights and suspension systems for cultivators was made by Russian and foreign researchers: I.V. Ignatenko, S.E., Fedorov, Krzysztof Lejman, Zbigniew Owsiak, Krzysztof Pieczarka, Franciszek Molendowski, A.B. Kudzaev, T.A. Urtaev et al [1-4, 6-11]. The use of the elastic uprights in the construction of cultivators helps to reduce the energy consumption and improve the quality of tillage.

The literature review showed that the design of the efficient elastic uprights and suspensions for interrow cultivators requires further improvement.

The analysis of the constructions of the elastic uprights and suspensions showed that they have a number of drawbacks that include heavy weight, insufficient stiffness for mounting of ridger frames, complicated construction of the safety systems and mechanisms for better stiffness of the elastic elements.

This provides the rationale for the design and production of the elastic suspension of the working body that is characterized by sufficient stiffness, reliability, lowest metal consumption and draught resistance.

1.1. Layout of the New Design of a Cultivator Section

To reduce the amplitude of vibrations of a tine in the horizontal plane, the elastic suspension can be designed as a closed-circuit mounting due to its equipment with a limiting clamp (Figure 1a).

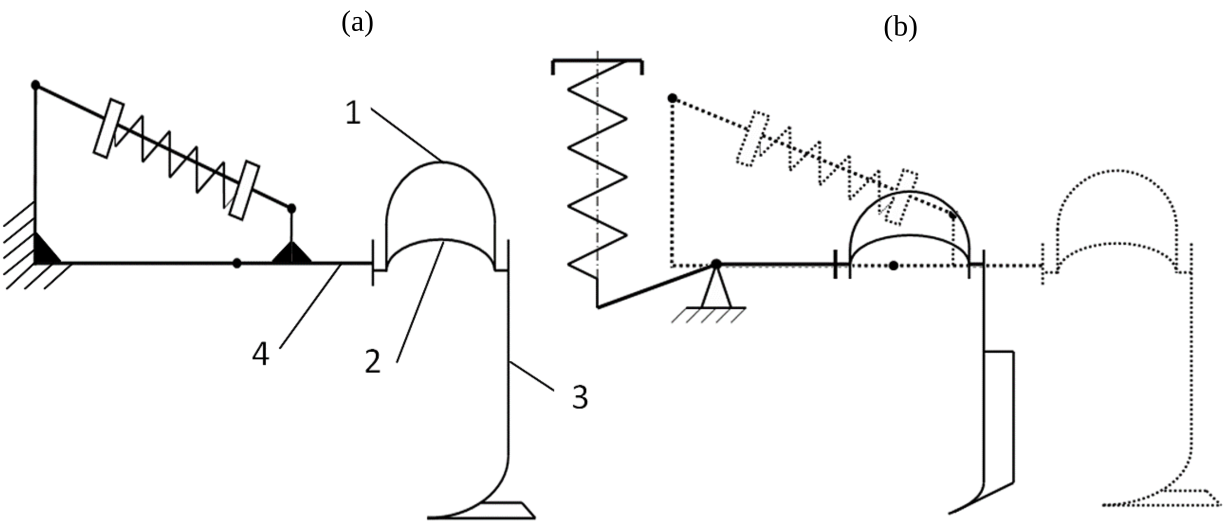


Figure 1. Constructive and technological layout of the section design upgrade: a) for the central working body; b) for side working bodies; 1- elastic suspension; 2- limiting clamp; 3- upright of the working body; 4- pivot bracket.

Figure 1a shows a constructive and technological layout for the central working body that is mounted on the elastic closed-circuit suspension. During the tillage, due to the changing resistance of the soil, the working body vibrates with the frequency that remains within the set limits, which contributes to the decrease in draught resistance and maintenance of the required depth of tillage. Facing an obstacle, an elastic suspension acts as a shock absorber that engages the safety system. The stiffness of the suspension can be changed by adding or removing additional clamps.

The depth of tillage is regulated by the change of uprights position in the holders and by means of the carrier wheel of the cultivation section.

2. Research Methodology

The study consisted of three stages. During the first stage, the approximate parameters of the proposed design were estimated by the theoretical calculations. During the second stage, the theoretical data were verified by the lab tests.

Experimental samples were designed and produced in the laboratory of the Department of Tractors and Agricultural machinery of the Gorsky SAU for the verification of the mathematical equation and determination of the main parameters of the suspension with satisfactory characteristics. A laboratory stand was constructed that allowed the researchers to measure the load that was applied to the endpoint of the working body and its movement in horizontal and vertical planes. A general layout of the stand is shown in Figure 2.

The authors installed a cultivator section with a limiting device and an elastic suspension mounted on the working body on the constructed stand frame (1) (Figure 2). The end of the working body was chained to the dynamometer (3) that was connected with a screw pair (2). The horizontal and vertical movements of the working body endpoint were measured by the rulers (4).

Natural vibration frequency was measured by the tension sensors (6) that were placed on the suspension. Their signals were transmitted to the laptop via a signal amplifier (7) and the analog-digital converter. The load P was gradually applied in the horizontal plane to the endpoint of the working body that was firmly mounted on the limiting device and its movements were measured in the horizontal and vertical planes.

The third stage of the experiment included the field trials of the elastic closed-circuit suspension during the interrow cultivation of maize. A special experimental section [5] was mounted on a tractor. During the field trials, the quality of soil tillage and the draught resistance at different depth and speed were evaluated. The trials were performed with the designed suspension of the working bodies mounted on a tractor model MTZ-80L on the 3rd, 4th, 5th and 6th gear, which corresponded to the speed 1.04, 1.29, 1.33 and 1.52 m/s, respectively.

Before the field trials, the authors collected the probes of soil according to the traditional methods. The soil samples were sent to the laboratory for the soil moisture measurement. Further, the soil hardness was evaluated by the hardness testing instrument. The cultivation section was fixed to the frame of the experimental section that was mounted by means of four tension rods with the pivots on the main frame [5]. A tensodynamometer was installed in the front part between the main and the additional frames. The horizontal load of the working bodies in soil was read by the tensodynamometer. Its readings were recorded via the amplifier and the analog-digital converter to the hard drive of a laptop and were shown on the screen in a form of the oscillograms. The readings were registered at the rate of 1000 times per second. For the convenience of the laptop charging, the experimental machine was equipped with an alternating current generator (220 V).

The tractor moved to the field, the depth of the cultivator was regulated, the tension measuring equipment was prepared. Further, the working process began and the studied parameters were registered. The experimental data were analyzed by the methods of mathematical statistics.

3. Results and Discussion

Theoretical studies were performed and mathematical correlations were obtained for the identification of rational values for the main parameters of an elastic closed circuit suspension.

For the calculation of the values of the horizontal stiffness of the proposed elastic closed circuit suspension design, the authors obtained the equation:

$$C_{гор} = \frac{EJ_X}{1{,}14 \cdot h_{cm} \cdot r_n^2} + C_{огр.} \tag{1}$$

Where

E = Young's modulus of elasticity, MPa;

J_x = Second moment of area, mm^4;

h_{cm} = Upright height, mm;

r_n = Upright radius, mm;

$C_{огр}$ = Stiffness of the limiting device, N/mm.

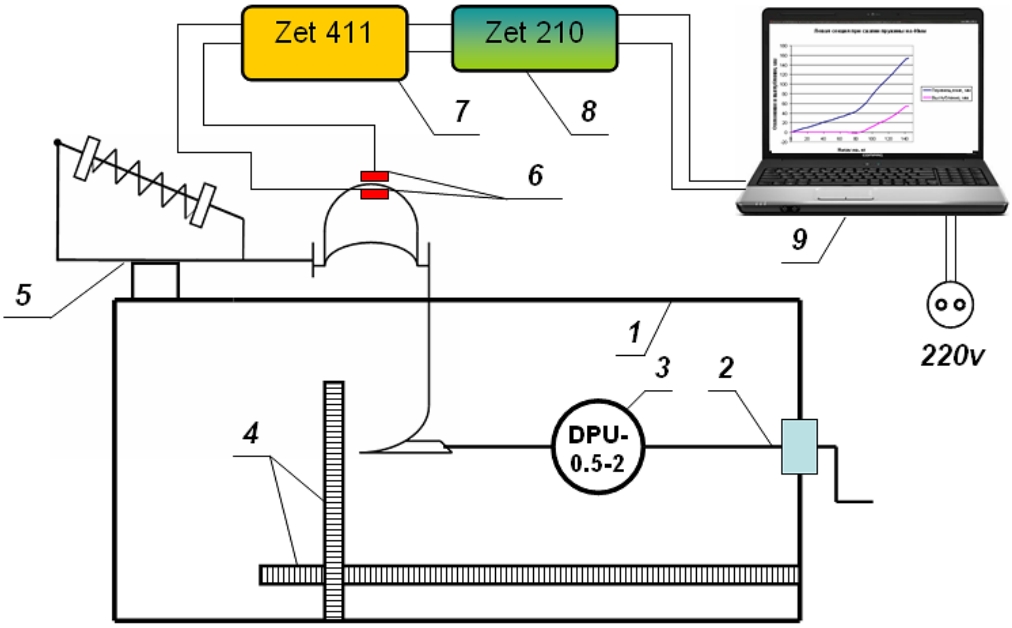


Figure 2. The layout of the laboratory stand for the evaluation of the stiffness and frequency of elastic uprights and suspension. 1- the stand frame; 2- tensioning unit; 3- dynamometer DPU-0.5-2; 4- measuring bars; 5- cultivator sections; 6- tension (strain) gauge; 7- amplifier; 8- analog-digital converter; 9- laptop.

At the first stage of the experiment, a single bow suspension with radius $R = 125\ mm$ and section $b \times h = 65 \times 10\ mm$ equipped with the limiting device of the analog section was tested.

Elastic bow suspension $R = 125\ mm\ (70 \times 10\ mm)$ had stiffness value equal to $6.69\ N/mm$. The error of the mean was 0.279 %. This stiffness ($6.69\ N/mm$) was insufficient for the mounting of the working body, so this upright design was excluded from further testing. These tests showed that it was feasible to increase the stiffness of the construction.

The next stage of the experiment included the evaluation of the suspension that consisted of two clamps with the radius $R_1 = 125\ mm$ and $R_2 = 135\ mm$ with the section $65 \times 10\ mm$. This construction provided significant shank out when facing major obstacles. Besides, two clamps significantly increased the stiffness of the construction. However, these tests showed that in this case, the researchers failed to increase the stiffness of the assembled construction either. The obtained stiffness was 8.2 H/mm. An insignificant increase in the construction stiffness was associated with the decrease in stiffness of the clamp and increase of the radium from 125 to 135 mm.

The tests showed that the application of bow closed-circuit suspension (without limiting device) was not feasible for the interrow cultivators.

Further, the tests of the closed-circuit suspensions were improved. First, elastic suspension with the radius R=125 mm and the section 70×10 mm and the limiting device with the section 65×10 mm were constructed. The test results showed that the coefficient of the horizontal stiffness of the given construction was equal to $C^{гор} = 21.9\ N/mm$ which was insufficient for mounting a ridger frame. To increase the coefficient of stiffness to 25 H/mm, the authors designed and constructed bow suspension that consisted of two clamps with the radius $R_1 = 125\ mm$ and $R_2 = 135\ mm$ and the section 65×10 mm, and the limiting device with the section 65×10 mm.

The tests on the movement of the endpoint of the working body mounted on a closed-circuit suspension are presented in Figure 3. To calculate the values of the working body endpoint shank out depending on the applied force, the following equation was obtained:

$$\delta_{верт} = -0{,}743 + 0{,}0055 \cdot P, (mm). \tag{2}$$

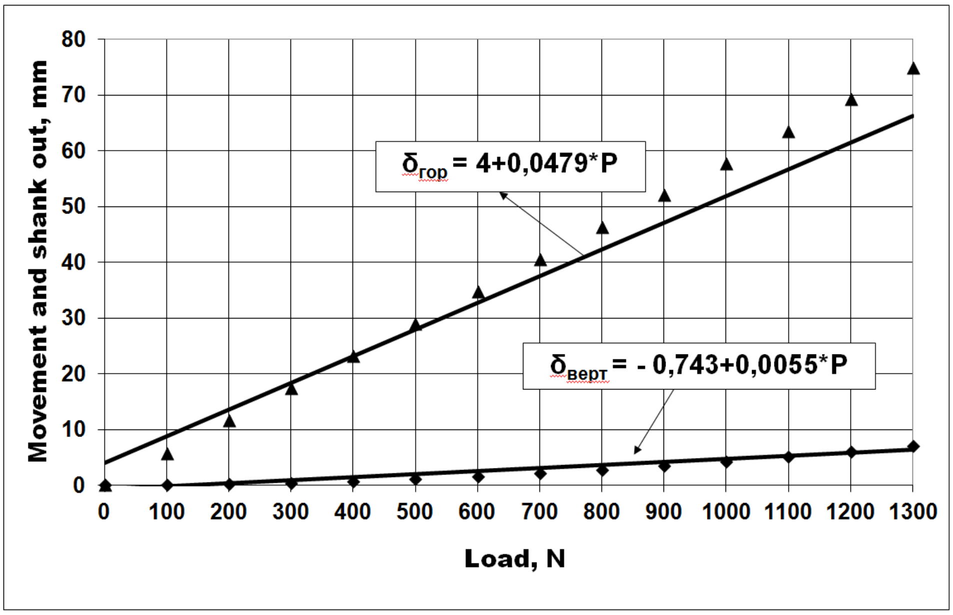
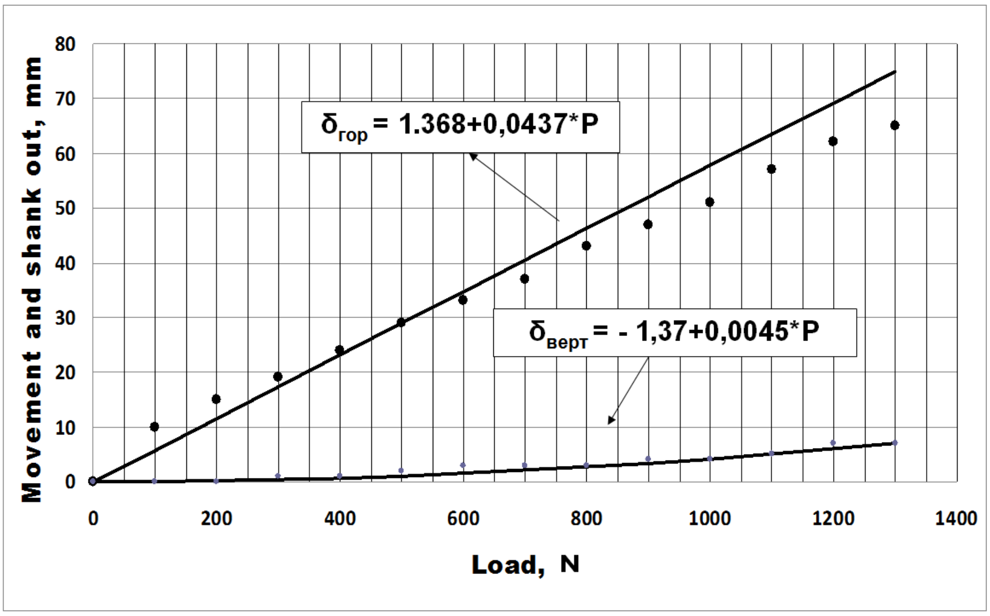


Figure 3. Correlation between the movement and shank out of the endpoint of the working body mounted on a closed-circuit bow suspension with the radius $R_1 = 125\ mm$, and the section $b \times h = 65 \times 10\ mm$, and the limiting device with the section $b \times h = 65 \times 10\ mm$ and the horizontal load.

The test results showed that horizontal load on the endpoint of the upright within the range of $P_{гор} \in [0 \ldots 1500]\ N$, the shank out of the endpoint was equal to $\delta_{выг} < 10\ mm$.



$^{\delta}$гор -$^{\delta}$horizontal, $^{\delta}$верт -$^{\delta}$vertical

Figure 4. Correlation between the movement and shank out of the endpoint of the working body mounted on the assembled bow suspension with the first clamp $R = 125\ mm$, the section $b \times h = 65 \times 10\ mm$, the second clamp $R = 135\ mm$, the section $b \times h = 65 \times 10\ mm$ and the limiting device $b \times h = 65 \times 10\ mm$ and the load

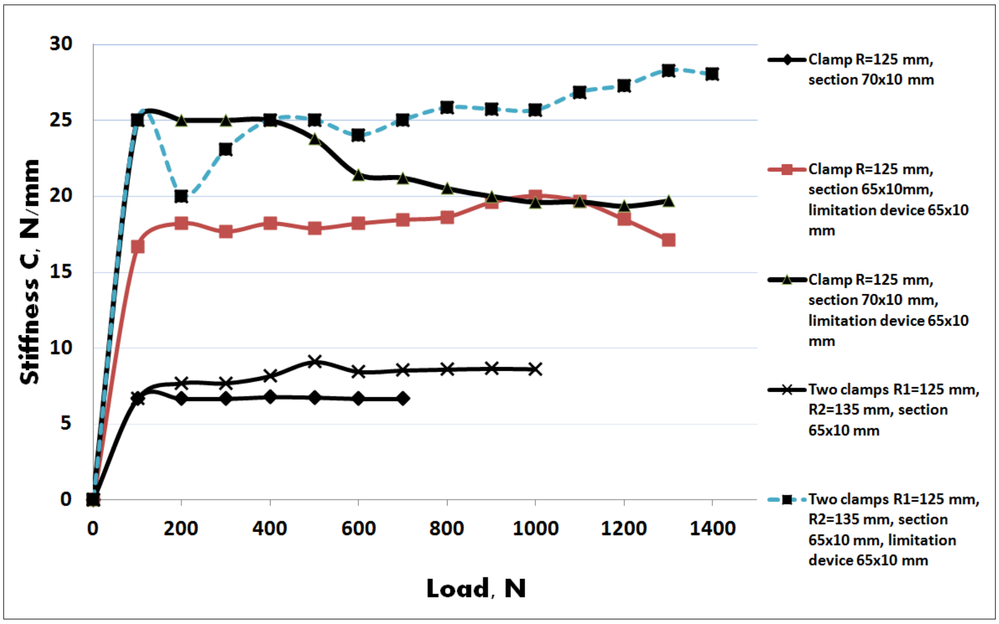


Figure 5. Change in the suspension stiffness under different loads

The graphs of suspension stiffness variations, observed during the tests, are presented in Figure 5. Two construction designs stand out among all the tested: a suspension with a clamp $R = 125\ mm$ and the section $65 \times 10\ mm$ with the limiting device $65 \times 10\ mm$ and a suspension that consists of two clamps with the radius $R_1 = 125\ mm$ and $R_2 = 135\ mm$, the section $65 \times 10\ mm$ and the limiting device with the section $65 \times 10\ mm$. The first suspension design is suitable for mounting the blades of the side working bodies, the second – for mounting of the central working body.

The central working body is recommended to have a bow closed-circuit suspension with the radius of bows $R_1 = 125\ mm$ and $R_2 = 135\ mm$, stiffness $C_{гор} = 25.6\ N/mm$ and frequency of vibrations ν∈[10.2…16.2] Hz. The side working bodies should have bow closed-circuit suspension with a limiting device with the stiffness $C_{гор} = 18.34\ N/mm$ and the frequency of vibrations ν∈[8.5…8.7] Hz.

a) b)

Figure 6. a) Experimental sample of an upgraded cultivator section equipped with a bow closed-circuit suspension; b) field trials of the experimental model with the cultivator section equipped with a bow closed-circuit suspension

Partly, the results are presented in Table 1.

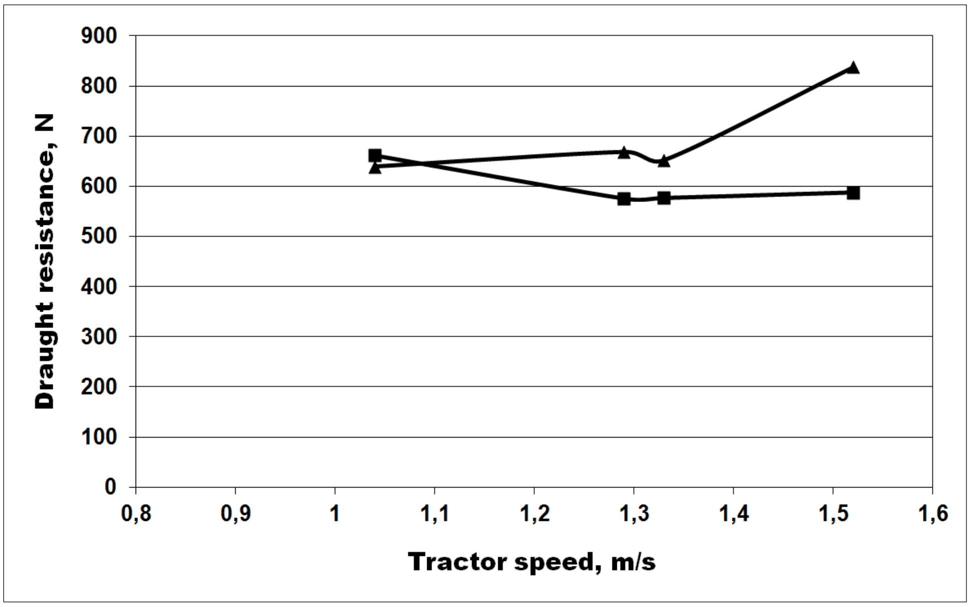


Figure 7. Correlation between the draught resistance of the one-sided tines mounted on the sections of the cultivator in a traditional way (1) and on a bow closed-circuit suspension (2). The depth of tillage was 3 cm.

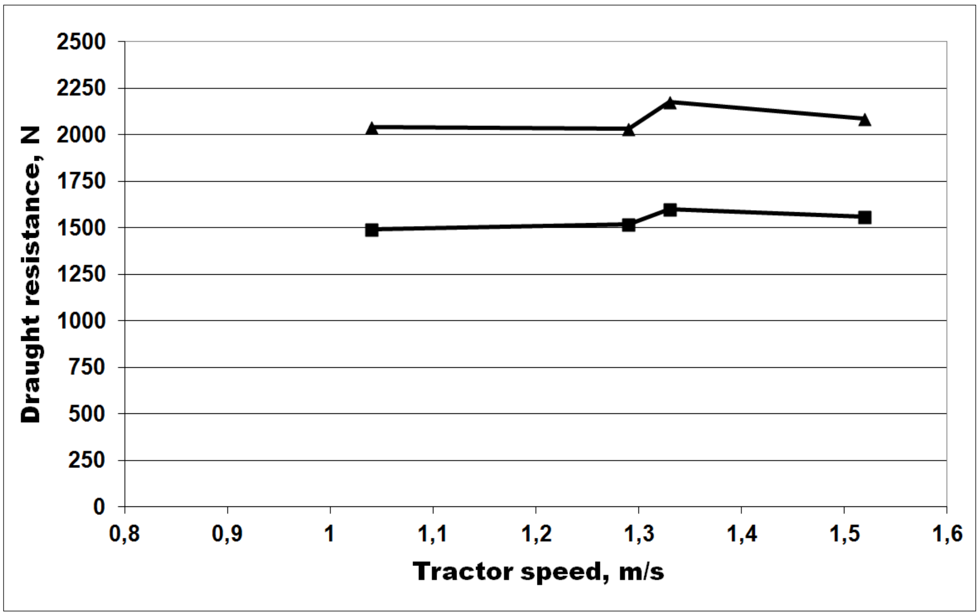


Figure 8. Correlation between the draught resistance of the ridged cultivator OK-3 mounted in a traditional way (1) and on a bow closed-circuit suspension (2). The depth of tillage was 12 cm.

Table 1. The results of the statistical analysis of the obtained data on the draught resistance of the cultivator working body with the elastic suspension and the variant of a firm mounting on the section

Working body	Depth of tillage, cm	Tractor gear	Draught resistance, N				
			Mean value, $\bar{X}$, N	Standard deviation, $\bar{\sigma}$, N	Variation V, %	Error of the mean, $S_{\bar{x}}$, N	Relative error, $S_{\bar{x}}$, %
Firmly mounted fertilizer blades	6	3	949.8	107.83	11.35	0.782	0.823
		4	1456.5	134.86	9.25	0.953	0.654
		5	932.5	118.82	12.67	0.706	0.757
		6	973.68	167.79	17.25	0.924	0.949
Firmly mounted fertilizer blades	9	3	1006.9	360.14	35.76	2.04	2.031
		4	900.241	192.32	21.36	1.149	1.276
		5	1110.6	198.37	17.86	2.37	1.69
		6	1118.2	260.23	23.07	1.92	0.37

Firmly mounted fertilizer blades	12	3	1167	287.67	24.6	1.689	1.44
		4	732.1	425.1	58.06	2.454	3.352
		5	1172.3	209.314	17.85	1.01	0.8696
		6	1549.8	362.06	23.36	2.024	1.305
Fertilizer blades on elastic suspension	6	3	656.7	116.8	17.79	0.7245	1.103
		4	846.5	179.9	21.25	1.272	1.502
		5	977.0	161.14	16.99	1.111	1.172
		6	948.4	163.2	17.27	1.032	1.093
Fertilizer blades on elastic suspension	9	3	937.8	182.2	19.43	1.130	1.205
		4	876.5	167.99	19.16	1.0844	1.237
		5	1093.5	177.4	16.22	1.692	1.546
		6	935.4	211.9	22.65	1.368	1.463
Fertilizer blades on elastic suspension	12	3	1091	202.51	18.55	1.025	0.939
		4	1130.9	157.78	13.95	1.088	0.962
		5	1055.8	172.38	16.32	1.322	1.252
		6	1202.7	207.33	17.24	1.311	1.090
Universal tine on elastic suspension	6	3	1099	254.56	23.15	1.445	1.314
		4	1093.26	183.79	16.81	1.027	0.939
		5	1147.6	215.51	18.78	1.265	1.103
		6	1169.8	189.99	16.24	1.311	1.121
Universal tine on elastic suspension	9	3	1082.1	161.97	14.97	1.322	1.222
		4	1027.1	198.28	19.30	1.891	1.841
		5	1197.5	200.14	16.71	1.827	1.525
		6	1299.84	313.1	24.08	4.427	3.405
Universal tine on elastic suspension	12	3	1195.6	242.74	20.30	1.22	1.024
		4	1272.3	139.7	10.93	0.93	0.735
		5	1320.3	168.33	12.74	0.84	0.637
		6	1310.4	210.49	16.06	1.14	0.869
Firmly mounted universal tine	6	3	1185	209.31	17.662	1.351	1.140
		4	1153	241.7	20.96	1.593	1.382
		5	1145	271.4	23.69	1.919	1.675
		6	1019.3	205.55	20.15	1.1186	1.163
Firmly mounted universal tine	9	3	1270	219.16	17.24	1.512	1.189
		4	1191	243.1	20.40	1.719	1.442
		5	1245.3	237.21	19.04	1.443	1.16
		6	1320.2	273.01	20.67	1.57	1.193
Firmly mounted universal tine	12	3	1203.4	159.45	13.24	0.905	0.752
		4	1321.3	157.42	11.91	0.941	0.712
		5	1369	261.13	19.06	1.507	1.100
		6	1403.2	246.96	17.59	1.301	0.927
Firmly mounted ridger frame OK-3	9	3	1726.9	199.42	11.54	1.41	0.816
		4	1780.4	189.90	10.67	1.11	0.626
		5	1513.9	202.06	13.34	1.92	1.272
		6	1376.3	220.07	15.98	1.86	1.351
Firmly mounted ridger frame OK-3	12	3	2042.4	365.03	17.87	2.41	1.178
		4	2031.196	211.78	10.42	1.49	0.737
		5	2177.4	287.58	13.21	1.718	0.789
		6	2085.88	260.71	12.49	1.481	0.709

Firmly mounted ridger frame OK-3	15	3	2439.6	409.06	16.76	1.972	0.808
		4	2684.0	448.4	16.71	2.679	0.998
		5	2054.7	422.8	20.57	2.621	1.276
		6	2352.2	447.8	19.03	2.952	1.255
Ridger frame OK-3 on elastic suspension	9	3	1608.7	246.97	15.35	1.359	0.845
		4	1620.3	241.997	14.93	1.312	0.809
		5	1624.2	229.22	14.11	1.479	0.910
		6	1629.3	248.81	15.27	1.259	0.773
Ridger frame OK-3 on elastic suspension	12	3	1494	263.57	17.63	1.497	1.001
		4	1517.6	285.6	18.82	1.596	1.052
		5	1600.5	317.8	19.85	2.686	1.678
		6	1557.8	298.9	19.18	2.062	1.324
Ridger frame OK-3 on elastic suspension	15	3	1865.3	463.27	24.83	1.975	1.059
		4	1899.1	295.5	15.56	2.09	1.100
		5	1878.6	291.07	15.49	1.878	1.00
		6	1984.0	307.28	15.48	1.870	0.942

It was shown that in comparison with the traditional option of mounting of the working bodies, the suspension of the proposed design reduced the draught resistance on average by 10…30% for the fertilizing blades, by 4.1% for universal tines, by 8.9% for one-sided weed-cutting blades, and by 15% for ridger frames.

The spectral analysis of the obtained data allowed the authors to determine the most significant frequencies of the vibrations of the working bodies. The graphs for the spectral density and standardized correlative function for one of the variants of the experiment are shown in Figure 9.

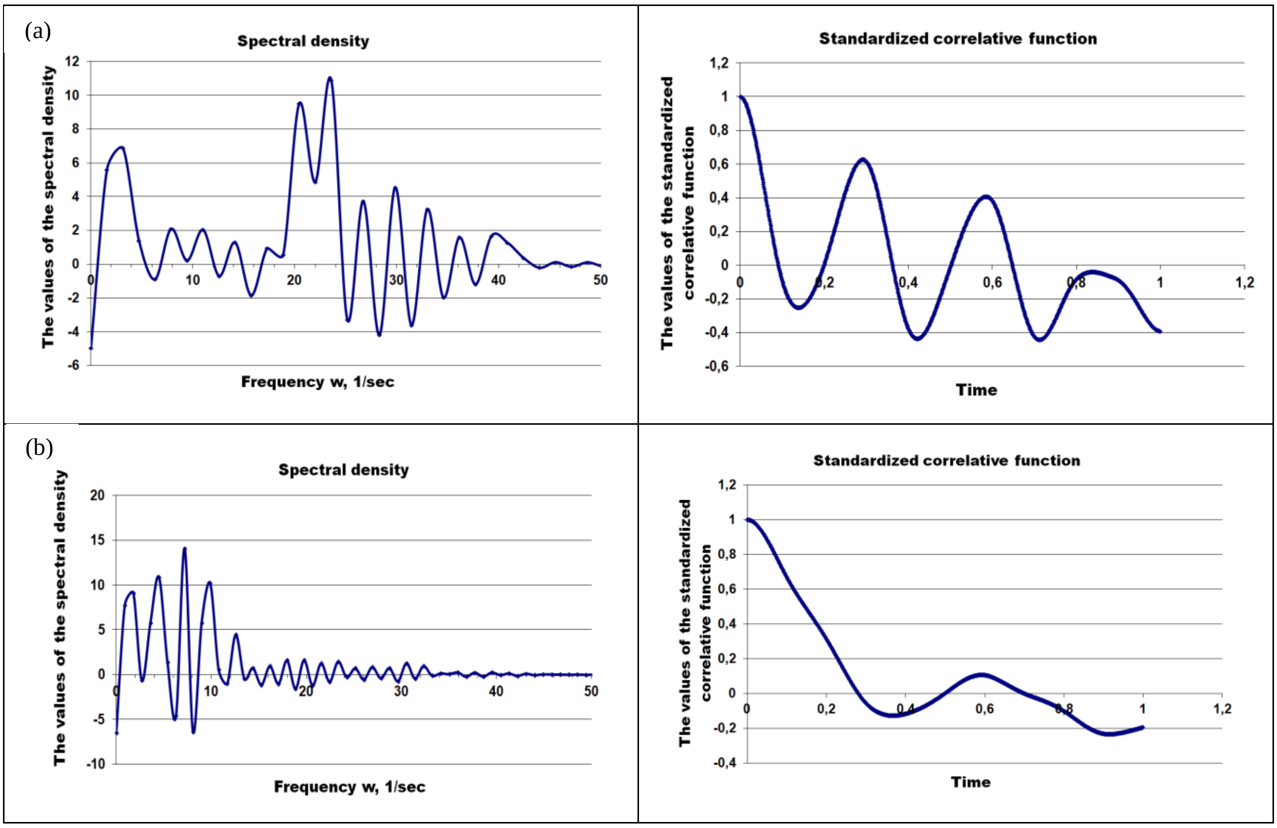


Figure 9. The graphs of the spectral density of the draught resistance and standardized correlative function of the cultivating working body that is equipped with firmly mounted fertilizer blades. The depth of cultivation was 0.06 m and the speed rate was 1.04 m/s: a) firm mounting; b) mounting on an elastic closed-circuit suspension

The obtained experimental results were implemented during the design and construction of a trial cultivator KRN-2.8 M "Gorets" that was successfully tested during the field trials. The quality of the soil cultivation was similar to the quality provided by the serial cultivators.

4. Conclusion

The study results showed that the designed construction of the elastic suspension are highly reliable and provide low shank out of the working bodies in the conditions of significant horizontal loads. This is explained by the fact that mounting different types of working bodies on the suspensions, the deviations in the depth of tillage remain within the agrotechnical norm ± 10 mm. However, this also suggests that a cultivator section has to be equipped with a safety device (for example, Figure 1) to be able to avoid the stones in the soil. The safety device shanks out the mounted working body when it faces a stone. Thus, the proposed design of an elastic suspension combined with a safety device allows the working body to move in the soil maintaining the uniform depth of tillage and to face the stones without technical breakdowns. The results of numerous field trials showed that the proposed construction of elastic suspensions better reduced the draught resistance for the working bodies in comparison with the models with the traditional mounting. It is important to mention that the reduction of the draught resistance was observed in trials with a cultivator equipped with fertilizing blades, tines and ridgers. This is provided by a proper horizontal stiffness of the elastic suspensions and the natural vibrating frequency. Thus, the proposed design of the elastic suspension for the central working body had the natural vibrating frequency $\nu \in [10.2 \ldots 16.2]$ Hz, and for the side working bodies - $\nu \in [8.5 \ldots 8.7]$ Hz. The study results showed that the suspensions operate in the frequency modes close to the resonance, which has a favorable effect on the reduction of the draught resistance of the working bodies. This statement is supported by the majority of the researches.

It should be noted that there is also another considerable advantage of the designed construction in comparison with the traditional models. A number of trials were conducted in severe conditions during the interrow cultivation of the droughty and stony soil. The working bodies mounted on the traditional elastic suspensions poorly penetrated the soil and the quality of tillage was unsatisfactory. When the working bodies were mounted on the proposed model of the elastic suspension, the quality of tillage met all the requirements. High quality performance is also provided by the chosen stiffness of the suspensions: for the central working bodies it was C_{hor}= 25.6 N/mm, for the side working bodies – C_{hor}= 18.34 N/mm.

It can be stated that the aim of the study was successfully achieved.

5. Funding

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6. Conflicts of Interest

The authors declare no conflict of interest.

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