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Study of a wide-level spring harrow with parallelogram suspension of the working section

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Abstract. Spring harrows have become widely used for surface tillage. A significant disadvantage of wide-level harrows is the unevenness of the loosening depth. The new design of the spring harrow with a parallelogram suspension of the working section copies the field microrelief to ensure a uniform loosening depth. The purpose of the study was to check the compliance with agrotechnical requirements of the spring harrow with a parallelogram suspension of the working section. To compile the mathematical model of the working section motion, use was made of the Lagrange equations. As a result, the authors determined the main adjustable technological parameters that affect the traction resistance and the depth of tillage. To verify the agrotechnical indicators, the authors designed a prototype of a spring harrow with the following adjustable parameters: the angle of the spring teeth (30°, 60° and 90°) and the force of the compensation spring unit (4, 6, and 8 kN). The wide-level spring harrow consisted of seven working sections with a width of three m and five rows of teeth with a pitch of 610 mm. The sections are attached to the longitudinal bracket of the frame by two pairs of rods at the front and rear of the frame. Field tests were conducted in the forest-steppe zone of the Southern Urals. Soil type was ordinary chernozem and heavy loam. During the tests, the depth of tillage, traction resistance and force of the adjustment spring block were measured. The traction resistance of a spring harrow with a working width of 21 m ranged from 19 to 45 kN. The average soil ridge after harrowing amounted to 3.4 cm, which meets agrotechnical requirements. Experimental studies have proved that the proposed harrow design satisfies agrotechnical requirements: it provides good soil crumbling at a tillage depth of 2 to 10 cm, stability of operation, and uniformity of loosening depth.

Keywords: wide-level spring harrow, traction resistance, tillage depth, traction resistance of spring harrow, soil ridging, soil microrelief copying

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Исследование широкозахватной пружинной бороны с параллелограммной подвеской рабочей секции

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Аннотация. Пружинные бороны получили широкое распространение при поверхностной обработке почвы. Неравномерность глубины рыхления является существенным недостатком широкозахватных борон. Разработанная нами конструкция пружинной бороны с параллелограммной подвеской рабочей секции позволяет копировать микрорельеф поля и обеспечивать равномерную глубину рыхления. Исследования проведены с целью проверки выполнения агротехнических показателей работы пружинной бороны с параллелограммной подвеской рабочей секции. Основные регулируемые технологические параметры, влияющие на тяговое сопротивление и глубину обработки почвы, определялись с помощью математической модели движения рабочей секции, составленной на основе уравнений Лагранжа. Получены зависимости тягового сопротивления и глубины рыхления от регулирующих параметров. Для оценки выполнения агротехнических требований был изготовлен опытный образец пружинной бороны, в котором с помощью винтового механизма регулировался угол наклона пружинных зубьев (30°, 60° и 90°) и менялось усилие блока компенсирующих пружин в диапазоне 4…8 кН. Широкозахватная пружинная борона состояла из 7 рабочих секций шириной 3 м и 5 рядами зубьев с шагом 610 мм. Секции крепятся к продольному кронштейну рамы двумя парами тяг в передней и задней их частях. Полевые испытания проводились в лесостепной зоне Южного Урала. Тип почвы – чернозем обыкновенный тяжелый суглинок. В процессе испытаний замерялись глубина обработки почвы, тяговое сопротивление и усилие блока регулировочных пружин. Установлено, что тяговое сопротивление пружинной бороны при ширине захвата 21 м варьируется в диапазоне от 19 до 45 кН. Средняя гребнистость почвы после прохода бороны составляла 3,4 см. Экспериментально доказано, что предлагаемая борона отвечает агротехническим требованиям: обеспечивает хорошее крошение почвы при глубине обработки от 2 до 10 см, стабильность работы и равномерность глубины рыхления.

Ключевые слова: широкозахватная пружинная борона, тяговое сопротивление, глубина обработки почвы, тяговое сопротивление пружинной бороны, гребнистость почвы, копирование микрорельефа почвы

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Introduction

Harrowing is a prescribed technological operation used to conserve soil moisture, crush the soil, level the background and distribute crop residues over the surface of the field [1-4]. Spring harrows have found wide application in the cultivation of agricultural crops. They are effectively used for loosening and leveling the soil, weed control, incorporation of mineral fertilizers and distribution of straw over the field surface [5-7]. Straw distribution is of great importance in No-Till technology [8-10].

Wide-level spring harrows have advantages over traditional rigid-type spike-tooth harrows. They have a large number of technological adjustments, cultivate soil with different agricultural background conditions and provide higher unit productivity. The disadvantage of wide-level spring harrows is the unevenness of the soil loosening depth. This drawback is explained by the poor adaptability of the spring harrow section to copying the unevenness of the field relief [11].

The uniformity of the soil cultivation depth depends on the width of the section and the method of its attachment to the implement frame. Spring harrows have a significant working width (21 m and more) for better tractor loading in terms of power. However, increasing the operating width significantly reduces the quality of soil cultivation due to uneven uniformity of deepening the spring teeth [12-13]. The method of attaching the working section to the frame is particularly important.

Our analysis of the designs of wide-level spring harrows has identified the following types of fastening of working sections to the frame (Fig. 1) [14]:

1. *Fastening the working section with chains*. The advantage of this method of fastening is good copying of the unevenness of the field surface microrelief. The disadvantage is the lack of impact on the vertical force of the soil-cultivating section. It is used on the BPG-24 spring harrow. However, the versatility of this machine is considerably lower due to the impossibility of making technological adjustments.

2. *Single-hinged attachment of the working section to the frame* (fig. 1b). This method of attachment used on the Morris and BPG-24.3 spring harrows allows changing the angle of attack of the tooth. However, the hinge increases the transverse unevenness of the processing depth and limits the possibility of technological adjustments.

3. *Rigid fastening of the working section.* Limitation of movement in the longitudinal vertical direction is carried out using loops to ensure a step change in the angle of attack of the teeth. This type of fastening is used on the spring harrows BZGT-8 "Pobeda".

4. *Fastening with a four-link parallelogram mechanism* implemented on the *SolomMaster-21* spring harrow (fig. 1d). The parallelogram mechanism ensures good copying of the field relief by the working section. However, the operation tests showed significant oscillations of the front and rear edges of the section frame during operation. The harrow also features excessive raising of spring teeth when passing over depressions and excessive deepening of spring teeth when

overcoming microrelief elevations [15-16]. This reduces the quality of soil cultivation.

In addition, the diagonally arranged compensating spring is not adjustable in this design. This harrow belongs to medium-type harrows used mainly for straw distribution, as its name implies.

To eliminate the previously mentioned drawbacks, the design of the harrow section with parallelogram suspension was developed [17, 18] (Fig. 2).

The working sections of the experimental harrow are positioned by means of two pairs of rods 4, pivotally fixed on the longitudinal bracket of frame 2. This technical solution ensures stable operation and uniform depth of soil cultivation.

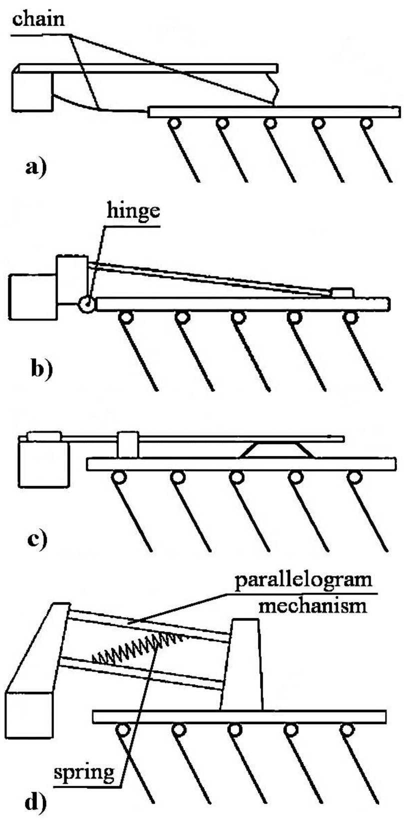

Fig. 1. Methods of fastening the working section to the frame: a – using chains; b – single-hinged; c – rigid fastening; d – on a parallelogram mechanism with a transverse spring

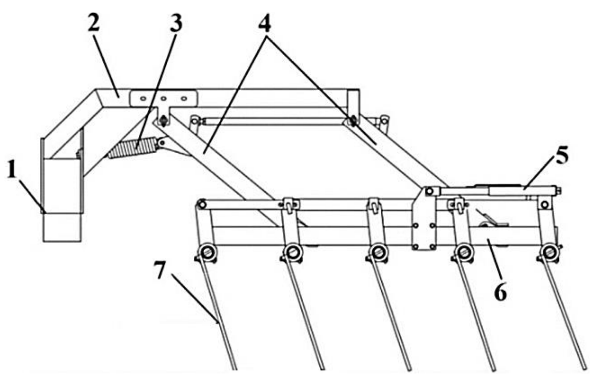

Fig. 2. Sections of a spring harrow with parallelogram suspension:
1 – frame; 2 – bracket; 3 – compensation springs; 4 – rods; 5 – spring strut angle adjuster; 6 – working section frame; 7 – spring teeth.

Additional adjustment of the inclination angle the spring teeth may change the depth of tillage up to 10 cm. We propose a screw-type regulator that uses the principle of a jack. One end of it is attached to the frame of the section and the other end is attached to the tooth support tubes. The screw mechanism changes the regulator length and provides the movement of the spring teeth hangers, thus changing their angles. Such mechanism provides smooth (instead of stepwise) setting of teeth angles in the range from 30 to 90 degrees. The proposed heavy harrow can be used not only for straw distribution, but also for soil loosening.

The reciprocating movement of the working section frame is independent of the harrow frame movement. This technical solution ensures that the spring teeth copy the unevenness of the soil surface. Uniform soil tillage depth is the main agrotechnical indicator of quality soil tillage during harrowing.

The research purpose is to check the performance of agrotechnical indicators of the spring harrow with a parallelogram suspension of the working section.

Materials and methods

Based on the Lagrange equation, we developed a mathematical model of motion that allowed us to identify the main parameters that influence traction resistance [19-20]. To check the compliance with agrotechnical requirements, a prototype of the working section of a spring harrow with parallelogram suspension was also manufactured (Fig. 2) and field tests were conducted.

During field tests, we measured tillage depth, traction resistance and force of the adjusting spring block.

Mathematical model of motion

Let us consider the forces acting on the working section of a spring harrow during soil cultivation (Fig. 3).

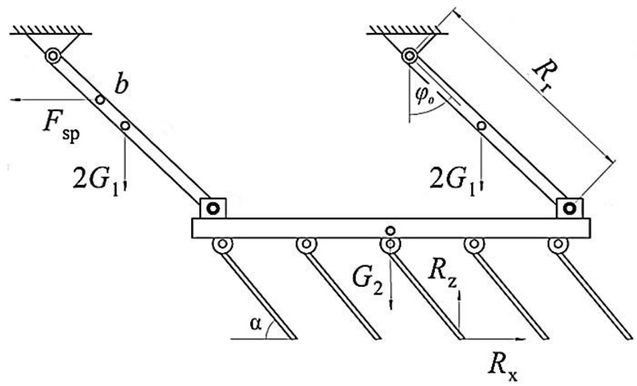

Fig. 3. Scheme of forces acting on the working part of a spring harrow with parallelogram suspension

Let us describe the forces acting on the working section:

– components of the external force R from the ground side on the spring tooth:

$$R_x = nR\cos(\alpha - \pi/2)$$
$$R_z = nR\sin(\alpha - \pi/2), \quad (1)$$

where α – the angle of setting spring teeth to the horizontal, degree; n = 5 – the number of spring teeth installed on the working section.

– elastic force of the adjusting springs is equal to:

$$F_{sp} = ch, \quad (2)$$

where c – spring stiffness, kN/m; $h = 2l_{ab}\sin(\varphi/2)$ – spring deformation, m; φ – inclination angle of the rods, deg; l_{ab} – length of the segment *ab* on the inclined rod (Fig. 3), defining the point of attachment of the spring on the rod.

– gravity forces:

$$G_1 = gm_1; \quad G_2 = gm_2, \quad (3)$$

where G_1, m_1 – weight and mass of the inclined rod; G_2, m_2 – weight and mass of the frame with spring teeth; g = 9.81 m/s$_2$ – acceleration of gravity.

The system has one degree of freedom. Under the action of forces, the inclined rods perform a rotational movement, and the frame of the working section with spring teeth performs a translational movement. If we take the angle φ of the inclined link deflection as a generalized coordinate, the equations of motion of the working section can take the form of [21]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}}\right) - \frac{\partial T}{\partial \varphi} = Q, \quad (4)$$

where φ, $\dot{\varphi}$ – generalized coordinate and generalized velocity; Q – generalized force, N; T – kinetic energy of the system, Nm.

The kinetic energy of the system is equal to:

$$T = \dot{\varphi}^2\left(\frac{2m_1R_r^2}{3} + \frac{m_2R_r^2}{2}\right), \quad (5)$$

where $\dot{\varphi}$ – the angular velocity of rotation of the inclined rod, 1/s; R_r is the length of the inclined rod, m.

The generalized force takes the following form:

$$Q = R_r sin\varphi\left(R_x - \frac{F_{sp}l_{ab}}{R_r}\right) + R_r cos\varphi(R_z - 2gm_1 - gm_2). \quad (6)$$

Substituting everything into equation (4) we get the equation of motion of the working section of the spring harrow:

$$2\ddot{\varphi}\left(\frac{2m_1R_r^2}{3} + \frac{m_2R_r^2}{2}\right) =$$
$$= R_r sin\varphi\left(R_x - \frac{F_{sp}}{k}\right) + R_r cos\varphi(R_z - 2gm_1 - gm_2), \quad (7)$$

where $k = l_{ab}/R_r$ is a design parameter characterizing the location of the attachment of the compensating springs.

Analysis of the solution of differential equation (7) allowed us to identify the main control parameters of the working section that affect the traction resistance of the working section: force of compensation springs F_{sp} and the operating angle of spring teeth relative to the horizon α (Fig. 3).

The traction resistance of the entire spring harrow was determined [22, 23]:

$$R_h = n_s R_x + G_h f, \quad (8)$$

where R_x – the traction resistance of one working section, kN; G_h – the weight of the spring harrow, kN; f – the coefficient of resistance to harrow movement.

Field tests

A prototype of an experimental spring harrow was manufactured to conduct field tests. The weight of a single working section was $G_1 + G_2 = 3.9$ kN. The inclined rods had a length of $R_r = 1$ m and an initial angle of inclination of 45°. The experiment was conducted in the forest-steppe zone of the Southern Urals of the Russian Federation (Fig. 4). The soil type is ordinary chernozem (black soil) and heavy loam.

Soil moisture at a depth of up to 5 cm was 19%, at a depth of 5-10 cm it was 27.7%. The soil hardness at a depth of up to five cm was 1.2 MPa, at a depth of 5 to 10 cm it was 1.5 MPa. The speed of the machine and tractor unit during harrowing ranged between 2.2 and 4.4 m/s. The soil was disc-cultivated before harrowing. The spring harrow's working depth was 4 to 8 cm.

Each working section was three m wide and included five rows of teeth with a pitch of 610 mm. The installation of seven working sections on a wide-level spring harrow provided a working width of 21 m.

The range of controlled parameters of the spring harrow was [24-25]: force of the adjusting spring block $F_{sp} = 4$ to 8 kN; angle of spring teeth to the horizon α = 30° to 90°.

Fig. 4. Machine-tractor unit with an experimental spring harrow during field tests

Results and discussion

An increase in the angle of inclination of the spring teeth α is accompanied by an increase in the depth *a* of processing of the spring teeth. The processing depth *a* increases by 3 cm with an increase in the operating angle of the spring teeth α by 30°.

Dependence diagrams between the tillage depth *a* and the angle of inclination of spring teeth α at different forces of the compensating spring block F_{sp} are shown in Figure 5. They are described by second-order polynomials with correlation coefficient R = 0.9994.

Increasing the force of the adjusting springs F_{sp} leads to additional deepening of the spring teeth. An increase in the loosening depth is characterized by an increase in traction resistance.

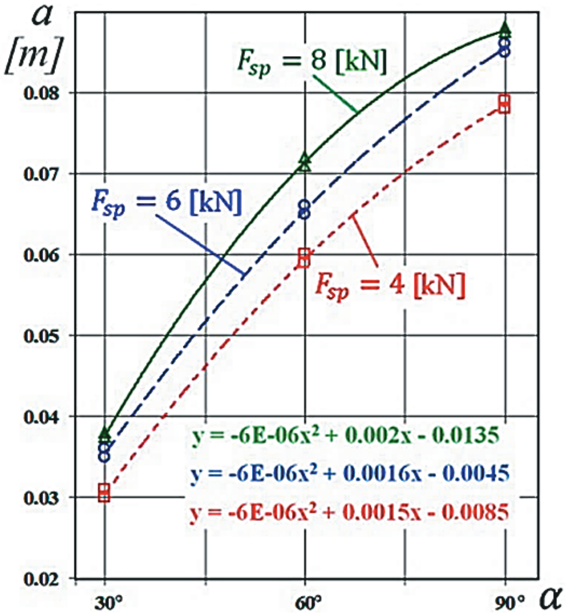

Fig. 5. Dependence of the soil tillage depth a on the angle of the spring teeth *a* at different forces of the compensating spring block F_{sp}

The relationship between the force of the adjusting spring block F_{sp} and the traction resistance R_x is linear. A consistent increase in the angle α from 30° to 60° and then to 90° contributes to an increase in the traction resistance of the spring harrow by 10 kN. It takes on values of 20 kN, 30 kN and 40 kN (Fig. 6).

An increase in the processing depth is accompanied by an increase in the traction resistance of the working section R_x. An increase in the force of the adjusting springs F_{sp} from 4 kN to 8 kN corresponds to an increase in the processing depth by 0.5 cm. The additional increase in processing depth is on average 1 cm, regardless of the operating angle of the spring teeth α.

Good uniformity of the working tool movement in depth has been experimentally established. The tillage depth varied from 8.7 cm to 9.3 cm at F_{sp} = 8 kN and angle α = 90°. According to GOST 33687-2015, tillage depth was measured for each section in at least 25 points along the movement trajectory. The scatter of values amounted to only ±3.5%. At the operating angle of spring teeth α=60°, the depth changes were observed in the range from 6 cm to 6.6 cm, which corresponds to the scatter of ±5%.

Good uniformity of soil cultivation depth is due to the design of the harrow sections, which allows copying the unevenness of the field microrelief. The average soil ridge after harrowing was 3.4 cm (Fig. 7). This meets agronomic requirements, as it is less than the standard ridge depth for a harrow, which is 4 cm [26]. The small value of ridging is due to the high looseness of the soil after preliminary disking.

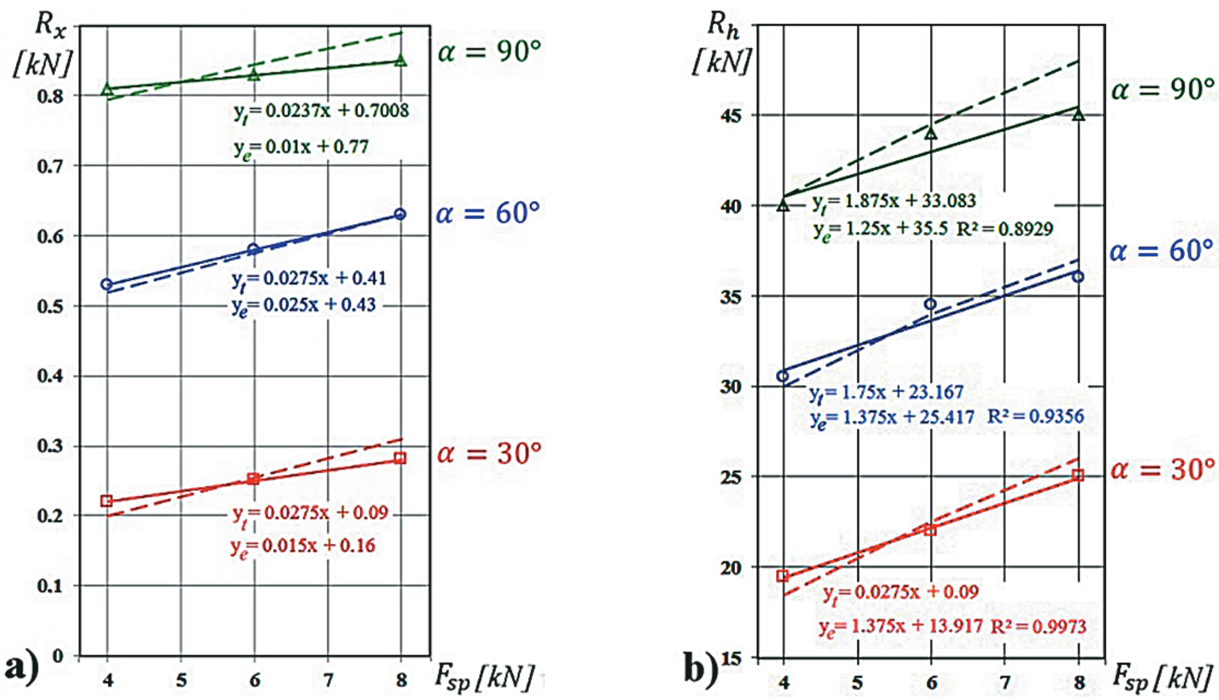

Fig. 6. Dependence of the traction resistance (a) of one working section and (b) of the entire spring harrow on the force of the compensating spring block F_{sp} at different angles of the spring teeth α:
——— experiment; – – – – theoretical

Fig. 7. Soil (a) before and (б) after tillage with a spring harrow

To evaluate the degree of crumbling, we introduced a crumbling factor

$$K_p = \frac{m_{25}}{m} 100\%,$$

where m – total mass of a soil sample, kg; m_{25} – mass of soil fractions up to 25 mm, inclusively, kg.

An improvement in soil crumbling was experimentally revealed depending on the operating angles of the teeth α. The proportion of soil fractions up to 25 mm in size increased from $K_p = 70\%$ to $K_p = 92\%$, with the angle α increasing from 30º to 90º. Increasing the force of the compensating spring block F_{sp} will further increase the percentage of soil crumbling.

Conclusion

We have developed a new design of the working section of a spring harrow with a parallelogram suspension. The use of a screw mechanism provides for smooth adjustment of the spring tooth angle in the range between 30° and 90°. The parallelogram suspension ensures better quality of copying of the working section with spring teeth relative to the harrow frame due to additional translational motion and gives additional possibility to regulate the loosening depth. The design novelty is protected by a patent of the Russian Federation.

We have offered a mathematical model of the working section movement to determine the adjustable process parameters that affect the traction resistance and designed a prototype. The angle of inclination of the spring teeth α can be set within the range of $30°; 60°;$ and $90°$. The force of the compensating spring block should change in the range of $F_{sp} = 4 - 8$ kN.

Field tests of a spring harrow with a parallelogram suspension were conducted to check the fulfillment of agrotechnical requirements. It was found that the proposed harrow ensures good soil crumbling at a soil cultivation depth of 2 to 10 cm.

The dependences of the traction resistance on the operating angle of spring teeth α and the force of the block of compensating springs F_{sp} were obtained. The traction resistance of the spring harrow with a capture width of 21 m varies in the range from 19 to 45 kN. The average ridge of the soil after the harrow passage was 3.4 cm, which meets the agrotechnical requirements.

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