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DETERMINING FORCES ARISING DURING THE PASSAGE OF COTTON FIBER BETWEEN THE FIXED KNIFE AND WORKING DRUM OF THE ROLLER GIN

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The object of this study is a roller gin. Roller gins are installed in the gin shops of cotton factories and their purpose is to mechanically separate cotton fiber from seeds in fine-fiber varieties of cotton. The criteria for the technological evaluation of roller gin are the sum of defects and fiber contamination after ginning, the cleansing effect of gin on weeds, damage to seeds, and fiber tow effects.

Existing methods do not fully reveal all the reserves of increasing the productivity of the machine, improving the design of the main working bodies of the roller gin, ensuring the effective operation of the machine, and preserving the natural qualities of fiber and seeds.

The determination of the force on the surface of the drum during the ginning process is of great practical interest for designing main working bodies of roller gins.

The efficiency and quality of the processed product depend on the interaction of the working drum and knife with the breaking organ in the process of fiber separation. The design of the drum and knife, their kinematic parameters, the stability of technological wiring largely determine both the performance of the gin and the quality of the fiber and seeds.

Theoretical studies have been conducted to determine the factors that affect the performance of roller gin. Based on the results obtained, it is recommended to change the most important structural parameters of the machine.

The obtained analytical expressions for the specific pressure and specific friction forces applied from the side of the drum surface to the processed mass of raw materials make it possible to conclude that when the load from the breaking body increases during the lower rebound, the process of grasping, dragging, and holding the fibers between the working drum and the fixed knife worsens

Keywords: roller gin, working roller, fixed knife of roller gin, breaking organ, drum design

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1. Introduction

The study of the work of roller gins first of all showed that the process of roller ginning is based on the interaction of raw cotton, a working roller, a knife, and a breaking organ. This is a component that ensures, at certain interaction, the separation of fiber from the seeds. At the same time, there are probably no physical foundations that could determine the spatial orientation of these four components of the ginning process.

The main working bodies involved in the ginning process are a working roller, a fixed knife, and a breaking organ.

The efficiency of the roller ginning process depends on certain physical and mechanical properties of the material of the working roller: a sufficiently high coefficient of friction, roughness, porosity, strength, the force of pressing the fixed knife to the working roller, the rotational speed and diameter of the working roller, the design and mode of operation of the breaker roller, the types of raw cotton processed, and its quality (humidity, contamination, etc.).

The strand of the fiber captured and pulled under the fixed knife is held back by the frictional force that occurs between the knife and the working roller with the fiber. A fixed knife is pressed to the working roller with a certain force and the fiber, pulled by the surface of the working roller under the fixed knife, is in the contact zone between the knife and drum. In this case, there are significant forces on the surface of the drum.

The issue of determining the forces on the surface of the drum during ginning is of great practical interest for the applied tasks related to constructing the main working bodies of roller gins.

2. Literature review and problem statement

The method for assessing the performance of a roller gin, developed in [1, 2] for roller gins with an inertial breaker organ, is more advanced. The method, along with structural factors – the speed of the breaking organ, the long working drum – takes into account significant factors that were previously ignored. These are the frictional properties of the working drum on the fiber and the knife on the fiber, the slippage coefficient of the working drum on the tightening fiber of the attachment of the fiber to the seed.

The disadvantages of the considered method of evaluating performance are that the most important structural parameters of the machine not taken into account – the stiffness of the knife, the elastic properties of the surface of the working drum, and the thickness of the pulled fiber. The pulling and ginning capacity of the working drum, and consequently, the productivity, as well as the degree of preparedness of the flyers fed into the ginning zone, significantly depend on them.

In works [3, 4], the formula for the performance of roller gin was derived, which serves as the basis for many other methods of performance evaluation developed later. The disadvantages of this method are that the performance formula does not take into account the factors that determine the gripping and pulling ability of the working drum and knife of the roller gin. Also, the most important structural parameters of the machine, the stiffness of the knife and the elastic properties of the surface of the working drum, the thickness of the pulled fiber bundles, the degree of attachment of the fiber to the flyer seed are not taken into account.

In more recent studies [5, 6], a method for assessing the performance of a roller gin with an inertial breaker organ was proposed, taking into account the separation of the fiber from the seed both by the breaking organ and by the work of the frictional forces of the ginning drum. The method for assessing the performance of a roller gin, developed in [7] for roller gins with an inertial breaker, is more advanced. The method, along with structural factors – the speed of the breaking organ, the length of the working drum – takes into account significant factors that were previously ignored. These are the frictional properties of the working drum on the fiber and the knife on the fiber, the slippage coefficient of the working drum on the pulling fiber of attachment of the fiber to the seed.

In works [8, 9], while examining the rebound forces of seeds on rigid and developed elastic breaking bodies, it was found that the average value of the rebound force for an elastic breaking organ is less than that of a rigid one by 4 N. It is proved that the inertial breaking organ does not make it possible to achieve high productivity since it is able to develop a force of 6 N, insufficient for the guaranteed break of the fiber bonds with the seed.

Works [10, 11] define the minimum speed of rotation of the breaker shaft, which provides the rebound force required for the complete exposure of seeds, equal to 0.12 kg (1.16 N). The necessity of dynamic balancing of the breaker organ in the optimization of the inertial breaker organ is also substantiated.

However, despite several works [6–10], the analytical description of the force effects that occur between a fixed knife and a gin working drum during the passage of cotton fiber in the contact zone is not yet fully represented in the available literature.

In work [12], the necessary mass of the hammer of the impact roller was established and the cause of the breakage of the leather shock absorbers was revealed, together with the formula for the performance of the roller gin.

Considering the effect of the design of the roller gin knife on the reliability of the ginning process, it should be noted that recently attention has been paid to the problem of reducing the friction of the fiber on the knife in order to increase the pulling force. In this direction, attempts are made to use the vibration of the knife. The friction of bodies on the vibrating surface is the subject of studies [13], which showed that the effective coefficients of friction of bodies, including cotton on the vibrating surface, are lower than the classical ones by 25–30 %.

According to study [6], with an ideal ginning process, the theoretical performance of gin can reach 600 kg/h, so it can be considered that the question of increasing the productivity of the machine by only searching for a material with high frictional properties is not the only one.

New opportunities to improve the efficiency of the process primarily include the study of the influence on the ginning process of such factors as the rigidity of the working drum-knife system of the breaker body structure, improving the conditions for capturing and pulling the fiber and the uniformity of feed.

The question of the influence of the quality of technological surfaces of the working elements of cotton ginning machines is investigated in [14]. And in study [15] it was shown that the effect of the stiffness of the drum surface on the ginning process was practically not examined. Some attempts to resolve this issue were made in work [16]. The uniformity of the compression density of the knife disc package along the forming drum has not been studied at all, and in fact the resulting friction forces against the shaft can significantly distort the picture.

In a number of works [17, 18], an analytical description of the force effects that occur between a stationary knife and a gin working drum during the passage of cotton fiber in the contact zone is not yet sufficiently represented in available papers.

In the studies, there are practically no generalizations of the main signs of the operability of the drum surface and a mathematical description of the influence on the process of ginning the parameters of the breaker body.

3. The aim and objectives of the study

The purpose of this study is to determine the forces that occur during the passage of cotton fiber between a fixed knife and a working drum. This will make it possible to find ways to develop the design of the roller gin and its working bodies to increase the efficiency of machines and preserve the natural qualities of fiber and seeds.

To accomplish the aim, the following tasks have been set:

– to determine the nature of the force effect on the element of the deformable material in the contact zone with the drum;

– to establish the law of distribution of the amount of specific pressure and specific friction on the fiber on the side of the drum and knife.

4. The study materials and methods

To create high-efficiency roller gins, it is necessary to deeply study the mechanics of the basic processes of interaction of raw cotton with the working bodies of gin. It is necessary to determine the reserves for improving the efficiency of the process of determining the forces arising during the passage of cotton fiber between a fixed knife and a working drum, as well as to investigate the mechanics of the seed rebound process and find new solutions to reduce their damage.

Identifying the influence of the parameters of the knife and the working drum and their interaction on the quality of the fiber, seeds, and the physical and mechanical properties of the fiber required experimental studies. Their ultimate goal is to determine the optimal technological and structural parameters of a fixed knife and working drum that ensure good quality fiber and seeds with high gin productivity. Experimental studies were conducted on a roller gin with a working length of the gin roller of 330 mm. The working roller is assembled from discs of RKM-2 material with a diameter of 180 mm, compressed with a force of 100 kN; the diameter of the breaking body was 115 mm, and the rigid knife had a thickness of 8.0 mm.

Studies have been carried out to determine the coefficient of tangential resistance of fibers on the surface of the working drum at low pressures. For the study, a device was used – a high sensitivity torsiometer, which through a flexible thread and clamp is connected to a flyer of cotton – raw material, located on the surface of the drum with a load. The working drum was driven into rotational motion (at speeds of 0.05–0.2 m/s) and, according to the readings of the torsiometer, the resistance force was determined.

The results of experimental studies are shown in Fig. 1.

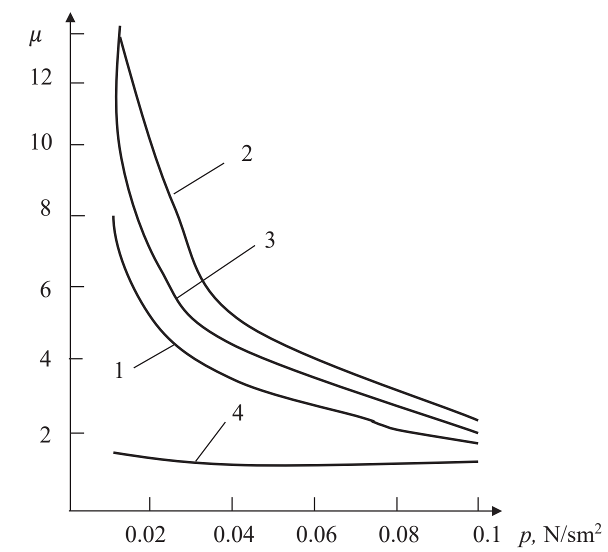

Fig. 1. Dependence plots of the coefficient of tangential resistance of fibers on the surface of the working drum at low pressures: 1 — tangential resistance coefficient for a newly sharpened drum from RKM-2; 2 — the dependence of change in the resistance coefficient on pressure during the relative movement of the flyer on the surface of the drum in the direction opposite to the direction of smoothing of micro-irregularities when interacting with the knife after processing; 3 — the dependence of the resistance coefficient on pressure at the same direction of relative motion as for case 2, for a working drum with a diameter of 150 mm after its operation; 4 — the dependence of the tangential resistance coefficient on pressure at the relative motion of the flyer and the resistance drum from the pressure at a relatively opposite direction compared to cases 2 and 3

As can be seen from Fig. 1, the coefficient of tangential resistance of the flyer fibers to the surface of the drum with their relative movement is much greater than in the opposite and reaches values within $\mu_1=2.0\div14.0$. The difference in the values of the coefficients is explained by the fact that the micro-irregularities during the interaction and burnishing of the drum with the knife are smoothed out in the direction opposite to the rotation of the drum and acquire a micro saw profile. Thus, the anisotropy of frictional properties is established. Thus, the anisotropy of frictional properties is established of the working drum of roller gin.

Drum stiffness must be optimized from the position of sufficiently increasing the pulling force, increasing the durability of the material, the resistance of the grooves, and preserving the natural qualities of the fiber.

Therefore, to increase the pulling effort, it is advisable to follow the path of increasing the stiffness of the knife. Obviously, the transition to a rigid knife on most modern gin designs will be justified as this will increase the technological reliability of the roller gin.

The transition to a rigid knife is restrained by the issues of manufacturing and heat treatment of knives, which must be solved by the manufacturer.

The considered issue is one of the significant reserves for increasing the ginning ability of roller gins.

Experiments were conducted according to the developed methodology [11]. The equivalent stiffness of the drum-knife system k_{eq} was changed by changing the stiffness of the surface k_1. The stiffness of the drum is related to the strengthening of the pressing of the leather disc package on the shaft σ and is represented in the form of a dependence plot k_1 on σ_b (pressing stress) and p_{0cp} (Fig. 2).

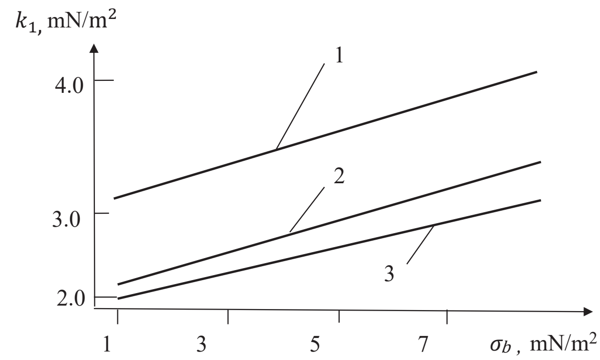

Fig. 2. Dependence of the stiffness coefficient of the drum surface on the compression stress of the disk package on the drum shaft: 1 — p=0.9 MH/m^2; 2 — p=0.7 MH/m^2; 3 — p=0.5 MH/m^2

As can be seen from Fig. 3, drum stiffness, k_1, hence k_{eq}, significantly affects the pulling force of the fibers. The calculated value of the force according to formula (9) is well confirmed by experimental data.

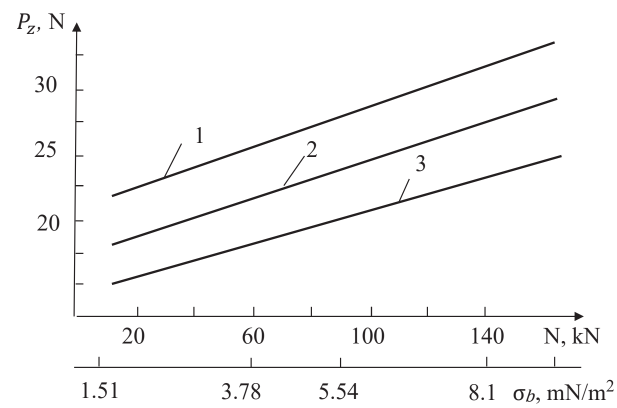

Fig. 3. Dependence of pulling force on the compression stress of the drum: 1 — p=0.9 MH/m^2; 2 — p=0.7 MH/m^2; 3 — p=0.5 MH/m^2

As a result of the a priori ranking of data obtained as a result of theoretical studies and preliminary experiments, the type of raw cotton being ginned, the stiffness of the drum surface, the speed of the working drum, and the speed of rotation of the breaking body were revealed.

The results of the experiments showed that with constant rigidity of the drum surface and contamination of raw cotton, an increase in productivity entails a deterioration in the quality of fiber and seeds. Fiber quality deteriorates mainly as a result of the growth of defects such as the peel with fiber and broken seed due to increased mechanical damage to the seeds. There is a slight increase in contamination due to dragging larger strands of fibers under the knife. The area of varying the productivity of the roller gin when converted to a meter width of the machine is taken from 80 to 120 kg/h.

One of the parameters characterizing its design is the malleability of the blades. According to preliminary experiments, the amount of malleability largely affects the damage to the seeds, the duration of slippage of the working drum along the fiber, the quality of the fiber. Preliminary tests suggest that the optimum malleability of the blade of the rebound body is between 0.05 and 0.0125 mm/N.

The speed of rotation of the breaking body affects the intensity of fiber separation, therefore, the productivity, the quality of the fiber and seeds. The impact on the qualitative indicators obliges to include in the experimental plan as a factor the rotation frequency of the breaking body. The variation interval is taken from 35 to 68 1/s, at which the specified performance is ensured.

Thus, all the factors identified as the main ones are quantified. The number of the main factors characterizing the operation of the stiffness of the drum surface is three. The total number of experiments in a complete factor experiment is 8 (excluding repetitions that reduce the errors of the experiment).

All factors vary on two levels (+1; –1), the number of experiments is 8 (without experiment in the center). Input variables and variation ranges are given in Table 1.

Randomization is used to partially compensate for the systematic errors of the experiment. Table 1 gives the levels of factors included in the experiment plan. After choosing the limits of variation, the order of experiments, etc., it is necessary to determine the output parameters by which it is possible to judge the operation of the machine, and which can become the starting point for optimizing the technological and structural parameters of the surface stiffness of the drum of the roller gin. For the output parameters of the experiment, values characterizing the quality of the fiber and seeds obtained during the ginning process are taken (Table 2).

Table 1

Input variables and variation ranges

Designation	Factors	Variation levels	
		–1	+1
x_1	Drum surface stiffness coefficient, MH/m^2	2.2	4
x_2	Working drum speed, m/s	0.05	0.2
x_3	Breaker speed,1/s	35	86

Table 2

Output variables

Designation	Output parameters
y_1	Broken seed, %
y_2	Peel with fiber, %
y_3	Nodules (neps), %

After the raw cotton was poured into the mine, the working drum was turned on, and after warming up for some time at idle, the working drum and power were turned on. After the experiment, the fiber and seeds, as well as the original raw cotton, were analyzed according to the accepted procedures of the state standard at the laboratory of textile materials science – AZS 151-2005 (Cotton fiber. Specifications).

The results of the experiments conducted according to the described procedure are given in Table 3.

Table 3

Experimental results and obtained regression equations

No. of entry	y_1	y_2	y_3
1	0.186	0.42	0.08
2	0.080	0.58	0.30
3	0.766	0.18	0.40
4	0.568	0.42	0.08
5	0.112	0.56	0.52
6	0.180	0.08	0.01
7	0.578	0.04	0.20
8	0.520	0.48	0.28
y_1=0.47+0.93x_1–0.218x_1x_2+0.282x_2–0.84x_2x_3+0.125x_3; y_2=0.324–0.074x_2x_3+0.158x_2+0.68x_3; y_3=0.152+0142x_1–0.68x_1x_2+0.84x_2–0.66x_1x_3+0.248x_3			

Comparison of data obtained during control experiments and calculations carried out on mathematical models confirms the correctness of the models and gives a satisfactory convergence with experimental data. The resulting system of equations allows for a directed search for the optimal parameters of both the technological process and the design of the working drum of the roller gin. Analysis of the fiber quality regression equations leads to the basic conclusion that the RCM-2 coating of the working drum structure does not damage the fibers and meets the production requirements.

As optimization parameters, the broken seed in the fiber, the sum of defects, and the increment of damaged seeds were selected with the following reference values y_1=0.6 %, y_2= 2.8 %, y_3=1.8 %, which corresponds to the permissible values of defects for the fibers of seeds of the first grade. The values of the coefficients are taken to be approximately equal to the significance of the parameters and correspond to: K_1=0.35, K_2=0.3, and K_3=0.35. Based on this, the objective function is obtained:

$$P=0.35(0.6-y_1)^2+0.3(2.1-y_2)^2+0.35(1.9-y_3)^2.$$

Optimization was carried out for each variety of raw cotton separately at a capacity of 120 kg/h. For raw cotton 5904-I, the optimal point has coordinates x_1=+1, x_2=–1, x_3=+1, at which P=0.140, and for raw cotton 9647-I – x_1=+1, x_2=–1, x_3=–1, at which P=0.11.

The results of the optimization make it possible to recommend capturing the fibers of the ginning flyer with the rough surface of the working drum and pulling it by the knife.

The cotton fiber from the gins with the new working drum had greater rigidity, which indicates a shorter residence time of the fiber, the flyers in the contact zone of the working roller and the knife due to the guaranteed rebound of the flyer seeds by the blades of the breaker body. This implies the possibility of increasing the performance of the roller gin. The high reliability of the working drum ensures the constancy of the gap between the drum and the knife, which reduces damage to seeds and broken seed in the fiber.

5. Results of the study of forces arising in the fiber between the fixed knife and the working drum

5. 1. Analysis of the force effect on the element of the deformable material in the zone of contact with the drum

Fig. 4 shows a diagram of the action of elementary forces arising in the contact zone of the knife with the drum during the passage of the cotton fiber. Below is an approach to the description of the behavior of cotton in the zone of its capture by the drum, based on the position that the mass of cotton between the drum and the knife is in a plastic state (due to the large forces of pressing the knife to the drum, larger than 0.12 N/cm^2, the gap in the contact pair during the passage of the flyer is very small 0.4 mm).

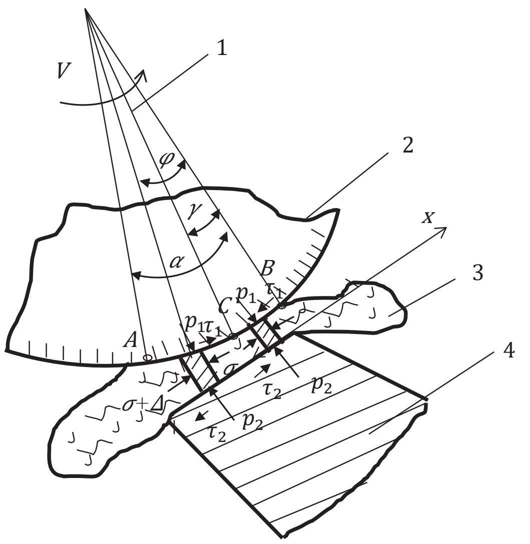

Fig. 4. Scheme of the passage of the flyer through the ginning contact knife-drum: AC-zone of the lag of raw materials from the rotation of the drum; CB-zone of advance: 1 – neutral cross-section; 2 – working drum; 3 – raw cotton; 4 – knife

As a result, one can use the equation of plasticity (the fourth theory of the limit state) [19]:

$$(\sigma_1-\sigma_2)+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2=2\sigma_s^2, \quad (1)$$

where σ_1, σ_2, σ_3 are the main stresses; σ_1 – yield strength; σ_2 – the average stress between σ_1 and σ_3.

If we assume that $\sigma_2=(\sigma_1+\sigma_3)/2$, then,

$$\sigma_1-\sigma_3=\frac{2}{\sqrt{3}}\sigma_s=1.15\sigma_s.$$

If we assume that $\sigma_2=\sigma_3$, then from the equation of plasticity for $\sigma_1-\sigma_3=1\sigma_s$ the following is obtained:

$$\sigma_1-\sigma_3=\beta\sigma_s=k, \quad (2)$$

where the coefficient $\beta=1-1.15$.

5. 2. Determination of the law of distribution of specific pressure and specific friction on the fiber from the side of the drum and knife

To construct the differential equation of state of the raw material with its two-dimensional deformation, the scheme shown in Fig. 5 is accepted.

The following designations are adopted in the diagram: σ – the average normal stress; p_1 – specific pressure at the arc point *ds* of the contact; τ_1 – the specific friction force at the point of the arc *ds* of the contact; p_2 – specific pressure from the knife; τ_2 – specific friction force from the knife.

In the presence of external forces *p* in the τ volume of the cotton fiber, the internal forces σ that balance them arise.

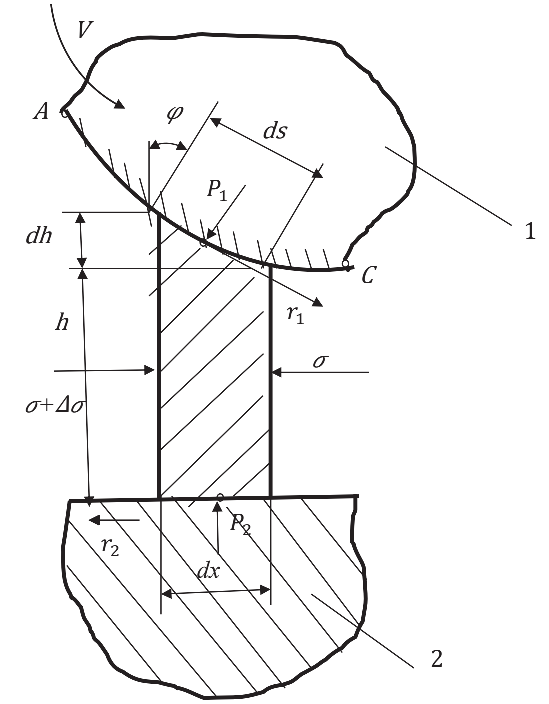

Fig. 5. Scheme of force action on the element of cotton fiber in the AC zone: 1 – drum; 2 – knife

When arranging elementary forces, it is necessary to proceed from the following kinematic conditions for the movement of the material between the drum and the knife:

1. On the surface of the drum, in the AC section (in the zone lagging behind the circumferential velocity V), the material is coupled to the surface but tends to move to the entry plane, which is due to the direction of the tangential force τ_1 (against the possible displacement of the material).

2. On the surface of the knife, the deformable material on the AB section constantly slides towards the exit, which is due to the direction of the frictional force τ_2.

To build a differential equation of the specific pressure forces from the side of the drum and knife on the fiber between them, a procedure from [14] was used.

To do this, the conditions of horizontal equilibrium of the element of the deformable material at the AC site were considered. In this case, on the *ds* section, the acting normal force will be p_1, and its projection onto the *x*-axis is $pds\sin\varphi$. Substitution of $ds=dx/\cos\varphi$ in this expression leads to $p_1 ds\sin\varphi=p_1\mathrm{tg}\varphi dx$.

The projection on the *x*-axis of the tangential forces acting on the element *ds* on the contact surface of the drum corresponds to $\tau_1\cos\varphi ds=\tau_1 dx$.

The sum of all the horizontal constituent forces acting on the raw cotton element is zero:

$$(\sigma+d\sigma)(h+dh)-\sigma h-p_1\mathrm{tg}\varphi dx+\tau_1 dx-\tau_2 dx=0,$$

where σ is the average normal stress; p_1 – specific pressure at the arc point *ds* of the contact; τ_1 – specific friction force at the point of the arc *ds* of the contact; p_2 – specific pressure from the knife; τ_2 – specific friction force from the knife.

If we neglect here the small values of the second order, taking into account $dx = dh/\text{tg}\varphi$, then an equation of the following form can be obtained:

$$d\sigma h + (p_1 - \sigma)dh + (\tau_1 - \tau_2)\frac{dh}{\text{tg}\varphi} = 0. \quad (3)$$

The sum of the projection of forces from the area *ds* of the drum onto a direction perpendicular to the *x*-axis is represented as:

$$p_1 ds \cos\varphi + \tau_1 ds \sin\varphi = p_1 dx + \tau_1 dx \text{tg}\varphi.$$

At the same time, the main vertical stress σ_1 acts on the *dx* site, which leads to a force $\sigma_1 dx$.

Hence,

$$\sigma_1 dx = p_1 dx + \tau_1 dx \text{tg}\varphi,$$

and it can be roughly assumed that $\sigma_1 \approx p_1$.

The main horizontal stress σ_3 is taken to be equal to σ. From formula (2), $\sigma_1 - \sigma_3 = k$ and then,

$$p_1 - \sigma = k,$$

$$dp_1 = d\sigma. \quad (4)$$

Substituting expression (4) into (3) results in an equation of the form:

$$dp_1 = \frac{dh}{h}\left(k - \frac{\tau_1 - \tau_2}{\text{tg}\varphi}\right). \quad (5)$$

Subsequently, in (5), the specific force of friction τ is expressed using Coulomb's law:

$$\tau = \mu p,$$

where μ is the coefficient of friction of the sliding.

Similarly, repeating all the above reasoning for the CB site (lead zone), an equation of the following form is obtained:

$$dp_1 = \frac{dh}{h}\left(k + \frac{\tau_1 + \tau_2}{\text{tg}\varphi}\right). \quad (6)$$

The solutions to equations (5) and (6) will be simpler and more approximate if you replace the variable $\text{tg}\varphi$ with constant values for the AC section: $\text{tg}\varphi = \text{tg}(\sigma+\gamma)/2$, for the CB section: $\text{tg}\varphi = \text{tg}\,(\gamma/2)$, where the angle of position of the neutral section γ can be determined further by selection.

If one enters the following notation in equality (5):

$$p\frac{\mu_1 - \mu_2}{\text{tg}\varphi} = p\frac{\mu_1 - \mu_2}{\text{tg}\dfrac{\varphi + \gamma}{2}} = p\delta_0,$$

then (5) will take the following form (hereinafter for simplicity the index at *p* is omitted):

$$dp = \frac{dh}{h}(k - p\delta_0).$$

Integrating this expression results in an equation of the following form:

$$p = C_0 h^{-\delta_0} + \frac{k}{\delta_0}. \quad (7)$$

From boundary conditions at a point A: $h = h_0$, $p = k$:

$$C_0 = k\left(1 - \frac{1}{\delta_0}\right)h_0^{\delta_0}.$$

Substituting the value C_0 in (7) brings the equation to the following form for the AC section:

$$C_0 = k\left(1 - \frac{1}{\delta_0}\right)h_0^{\delta_0}. \quad (8)$$

Next, the following notation is introduced into equation (6):

$$p\frac{\mu_1 + \mu_2}{\text{tg}\varphi} = p\frac{\mu_1 + \mu_2}{\text{tg}\dfrac{\varphi + \gamma}{2}} = p\delta_1.$$

Repetition now for the ratio (6) of all the above reasoning on integration (5) leads for the section CB (at which the boundary conditions at point CB: $h = h_0$; $p = k$) to the equation:

$$p = \frac{k}{\delta_1}\left[(\delta_1 + 1)\left(\frac{h}{h_1}\right)^{\delta_1} - 1\right]. \quad (9)$$

As a result, analytical expressions (8) and (9) for the law of distribution of the specific pressure *p* at the ACB section of the drum gripper are obtained.

Consideration should be given to the case where there is a preliminary initial tension σ_A at the leading end at point A.

To determine the integration constant C_0 in formula (7), the initial condition at end A would look like this: $h = h_0$; $p = k - \sigma_A$.

Further, *p* can be represented as $p = k - \sigma_A = k\xi_0$. Here $\xi_0 = 1 - \sigma_A/k$, $0 < \xi_0 < 1$. In the absence of tension at the front end, $\sigma_A = 0$ and $\xi_0 = 1$:

$$C_0 = k\left(\xi_0 - \frac{1}{\delta_0}\right)h_0^{\delta_0}.$$

Substituting C_0 into expression (7) leads to the law of change in specific pressure in the lag zone AC:

$$p = \frac{k}{\delta_0}\left[(\delta_0\xi_0 - 1)\left(\frac{h_0}{h}\right)^{\delta_0} + 1\right]. \quad (10)$$

For the CB section is the lead zone, the pattern of change in specific pressure *p* is expressed in the previous form (9).

The obtained analytical expressions (8) to (10) make it possible to construct diagrams of specific pressure *p* (Fig. 6) and specific friction τ, acting from the side of the drum surface on the processed cotton mass.

Subsequently, in (5), the specific force of friction τ is expressed using Coulomb's law $\tau = \mu p$. From Fig. 1 it can be concluded that the plots of the dependence of change in the resistance coefficient on pressure with the relative movement of the flyer on the surface of the drum decrease.

If it is assumed that the sliding of the material on the surface of the drum and knife occurs under dry friction (Coulomb's law), then the tangential contact stresses τ on the surface of the drum are proportional to the specific pressure *p*:

$$\tau = \mu p. \quad (11)$$

As can be seen from the presented diagrams, in the presence of tension σ_A at the edge of a fixed knife (near point A), point C of the maximum pressure of the drum on the fiber moves towards point D. In the same direction, the neutral point D of the specific friction forces τ shifts accordingly.

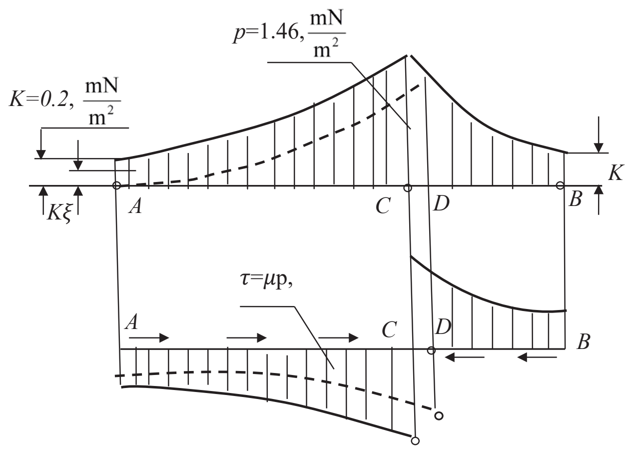

Fig. 6. Specific friction distribution diagram τ on the surface of cotton raw materials along the capture arc

From the foregoing, it can be concluded that with an increase in the load on the fiber from the breaking body at point A, the processes of capturing, dragging, and holding the fiber between the working drum and the fixed knife deteriorate.

6. Discussion of results of the study of the force effect on the element of the deformable material

When calculating the dynamic separation of fibers from the seed when the breaking body is hit, it must be borne in mind that in the real process, the fibers in the strand are very heterogeneous and unevenly stretched when they are dragged into the slot of the contact gap of the knife-drum. The separation of fibers from the seed after the impact of the breaking body does not occur simultaneously, but sequentially, either in separate fibers or groups thereof, usually in 3–4 strokes of the breaking body.

Analyzing the effect of the tangential resistance coefficient on the fiber capture process, it should be noted that a more reliable capture of fibers is carried out by the working drum. This occurs when the fibers interact with the posterior faces of micro-irregularities in the AC zone (the zone of lagging behind the rotation of the drum of the raw materials) (Fig. 4).

This is possible when the relative velocity of the drum is less than the speed of the flyer. It can be concluded that with an increase in the load on the fiber from the breaking body at point A, the processes of dragging and holding the fiber between the working drum and the fixed knife deteriorate.

Works [15, 16] give complex methods for assessing the performance of a roller gin, which take into account the most important structural parameters of the machine: the stiffness of the knife, the elastic properties of the surface of the working drum, the thickness of the pulling beams of fibers, on which the pulling and ginning ability of the working drum significantly depends, as well as the degree of preparedness of the flyers fed into the ginning zone. The main reasons for these and other imperfections of the processes of primary processing is that when designing roller machines and establishing modes of technological processes, the basic physical, mechanical, and other properties of raw cotton are largely neglected. Research into such fundamental areas as modeling the laws of deformation and change of shape, volume of raw cotton under the influence of static and dynamic loads has not been completed.

In [17], when studying the capturing ability of the surface of the working roller, they revealed the optimal ratio of speeds and rotational speeds of the breaker and working rollers depending on the number of blades of the bump roller.

Thus, before approaching the contact zone with the knife, due to the presence of accelerations, there is a dynamic «shaking» of the surface of the working drum, which can significantly affect the conditions for capturing cotton fibers with micro-irregularities and pulling them behind the knife. The dimensions of the edge of the knife and the amount of deformation of the surface of the drum with the knife are commensurate. Thus, the radius of curvature of the edge of a new knife is ρ_{max}=0.5: in the process of wearing the knife by 0.1 mm, and the deformation of the drum surface, depending on the conditions of its formation by compression, it is from 0.1 to 0.6 mm. Therefore, depending on the ratio of the amount of deformation and the size of the edge of the knife, various cases of interaction of the drum with the cotton fiber and the knife are possible, directly affecting the conditions between the fixed knife and the working drum. Obviously, the greater the amount of deformation and the smaller the thickness of the edge of the knife, the greater the effect of «shaking» will be, due to which the capture of the fibers worsens.

From the obtained expressions (8), (9) it follows that the greatest acceleration of the surface of the drum will be at the beginning of contact with the knife, i.e. at point A and its surroundings. If the thickness of the edge of the knife blade is significantly less than the amount of deformation of the drum, then the shaken fibers from the surface of the working drum will bypass the knife and go with the flyer to regeneration, that is, the fibers will not fall into the contact zone of the drum with the knife.

If the thickness of the edge of the blade is commensurate with the deformation, then an active pulling wedge ABE is created between the surface of the working drum and the knife (Fig. 4), which significantly improves the gripping conditions, since, even by shaking off the fibers from the surface of the drum near point B, due to the reactive force of reflection from the knife, they can again be captured by micro-irregularities and pulled behind the knife.

A significant increase in the thickness of the edge is unacceptable since the edge of the knife in this case becomes an obstacle to the movement of seeds and can serve as an anvil when hit by a breaking body on the seeds, which will lead to a sharp increase in their damage.

If we consider this process from the point of view of two types of rebound – the so-called lower and traditional rotational type, then preference should be given to the second. This is explained by the fact that during rotational rebounding, the blade, moving in the same direction in which the fiber is dragged under the stationary knife, contributes to the bending of the edge of the fixed knife with the fiber and the emergence of additional friction forces τ.

As a result, the neutral point of specific friction forces is shifted in the direction of the edge of knife A and the ginning force of the working drum-fixed knife pair increases.

It should be noted that in addition to (11), other points of view on the nature of friction along the capture arc are also known, namely:

1. Frictional forces are taken to be proportional to the sliding speeds (Newton's law of viscous friction).
2. Frictional forces along the capture arc are constant.

The question of which law of friction and in which section of the gripper is actually implemented in this mode of operation of the roller gin requires special research.

Ratios (8) to (11) make it possible to construct theoretical diagrams of the distribution of specific pressure p and specific friction τ along the capture arc, that is, to determine the surface forces distributed along the drum at the location of the knife.

The disadvantages of existing methods [14–18] are that factors such as the distribution of specific pressure and specific friction on the fiber from the drum and knife are not taken into account. Also, the most important structural parameters of the machine are not taken into account, such as the location of the knife relative to the working drum, as well as the thickness of the pulling fiber bundles and the degree of attachment of the fiber to the flyer seed.

To eliminate these shortcomings, theoretical and experimental studies of the factors of influence on the performance of roller gin have been carried out. Based on the results obtained, it will be possible to change the most important structural parameters of the machine.

It should be noted that the limitations of this method are that experimental studies were conducted for raw cotton fibers with a length of 40–42 mm, and, with a length of 43–46 mm, it is necessary to conduct experimental studies with a change in the diameter of the working drum of the roller gin, i.e. to change the length of the arc AB.

7. Conclusions

1. The nature of the force effect on the element of the deformable material in the contact zone of the knife with the working drum has been determined. On the surface of the drum, the zones of lag and advance of the fibers from the circumferential velocity of the drum are determined. The study of the pressure distribution in the contact zone of the knife with the working drum made it possible to determine not only the strength of the pulling of the fibers but also the nature of the force effect on the element of the deformable raw cotton necessary to calculate the durability of the rubbing materials. This will help to uncover the fiber capture mechanism of the working drum and determine the optimal coordination of the knife.

2. Analytical expressions have been obtained for the law of the distribution of the value of specific pressure p and specific friction τ on fiber from the side of the drum and knife at the ACB site. Based on the results of theoretical studies, it can be concluded that a small amount of specific pressure and high specific friction on the fiber from the side of the drum and knife lead to an increase in productivity, and this entails a deterioration in the quality indicators of fiber and seeds. Fiber quality deteriorates mainly as a result of the growth of defects such as the peel with fiber and broken seed due to increased mechanical damage to the seeds. Reducing the amount of specific pressure leads to an increase in contamination due to dragging larger strands of fibers under the knife. The results obtained make it possible to recommend improving the conditions for capturing fibers with a drum and pulling them by the knife by determining the ratio of the speeds of the breaker body and the working drum.

Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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