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Theoretical Foundations of The Fiber Separation Process in A Laboratory Roller Gin of a New Design

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Abstract: The article presents the theoretical foundations of the fiber separation process from the seed in a newly developed laboratory roller gin intended for ginning small samples of raw cotton. The gin design includes a working roller and a double-knife system, consisting of a stationary and a movable knife located in the ginning zone. Based on a force analysis of the fiber section clamped between the stationary knife and the ginning roller, expressions are derived for the friction forces, the normal pressing force, and the resultant force tending to detach the fiber from the seed. It is shown that, with friction coefficients of 0.463 between the fiber and the leather roller and 0.32 between the fiber and the knife surface, the detaching force amounts to about 14.3% of the normal pressing force. It is established that the movable knife introduces a periodic dynamic component into the detaching force, while the alternating stresses in the fiber attachment zone cause fatigue weakening of the bond between the fiber and the seed. The conditions for effective fiber separation and for avoiding fiber damage are formulated, defining the permissible combinations of system parameters. On the basis of the force analysis, a mathematical model is constructed that describes the dynamics of fiber separation under the action of the working elements of the double-knife system. In this model, the fiber tuft (lint fly) is treated as a material point moving under friction, aerodynamic drag, and damping forces. An analytical solution of the linearized equation of motion is obtained, which makes it possible to determine the trajectory of the fiber tuft and to distinguish the transient, uniform, and oscillatory components of its motion. Expressions are derived for the critical displacement of the fiber tuft and for the fiber separation time, which is inversely proportional to the normal pressing force and to the difference between the friction coefficients, and directly proportional to the mass of the fiber tuft and the bond strength between the fiber and the seed. Optimality criteria and an expression for gin productivity that includes an intensification coefficient are proposed, providing a basis for optimizing the design and operating parameters while ensuring the required fiber quality.

Keywords: Roller gin, ginning, knife, tension, friction, fiber tuft (lint fly), impact, equation, resistance, mathematical model.

1. Introduction: Roller ginning is the main method of primary processing of fine-staple cotton, since it ensures the maximum preservation of the natural properties of the fiber: according to [1], mechanical damage to the fiber during roller ginning is 2–3 times lower than during saw ginning. Comparative studies have shown that, when ginned on a roller machine, the fiber yield, length, uniformity index and breaking load are higher than when ginned on a saw gin [2]. At the same time, the main drawbacks of roller gins remain their low fiber productivity and seed damage [1].

The process of separating fiber from the seed is of particular importance in seed production. On elite seed-growing farms, the seed cotton of each family

(about 60–85 g) must be ginned separately, without mixing the seeds of different families [4–6]. The ten-saw laboratory gins of the DL-10 type used for this purpose require, by their operating principle, the formation of a seed-cotton roll in the working chamber, which calls for at least 0.5–0.8 kg of raw cotton and its continuous feeding; therefore, ginning samples weighing several tens of grams on them is practically impossible, and when such samples are processed anyway, the increase in mechanical damage to the seeds exceeds 1.3%.

Theoretical studies of roller ginning are developing in several directions. In [1], the conditions of fiber capture and draw-in by the "working drum – stationary knife" system were considered: it was shown that the pulling force is determined by the product of the normal pressing force and the difference between the friction coefficients of the fiber against the drum and against the knife, and that the fiber is detached when this force exceeds the force holding the fibers on the seed; analytical expressions for the specific pressure and friction forces were obtained, and it was shown that an increase in the load from the beater element impairs the capture, draw-in and retention of the fibers. The dynamics of the "fiber – seed" separation under the impact of the beater element was studied in [7]: the fibers are separated successively, and a mode close to resonance makes it possible to reduce the magnitude of the impact impulse and the degree of seed damage. In saw gins, the dynamic loading of the fibers is associated with the difference between the speeds of the saw cylinder and the seed-cotton roll [8], and seed damage and fiber quality are associated with the density and rotation speed of the seed-cotton roll [9, 10].

At the same time, the theoretical works considered [2, 10] mainly study industrial roller and saw gins designed for the continuous processing of large batches of raw cotton. Laboratory roller gins for the separate ginning of small samples, and in particular two-knife systems with a movable knife performing oscillatory motion along the roller surface, have not been considered theoretically in these works; moreover, the influence of knife oscillations on the fiber separation time and on gin productivity has not been assessed quantitatively.

The aim of this work is a theoretical description of the process of separating fiber from the seed in the developed laboratory roller gin with a two-knife system, the construction of a mathematical model of the dynamics of the fiber tuft, the derivation of expressions for the fiber separation time and gin productivity, the determination of rational parameters of the movable knife, and the verification of the main results by laboratory and production tests.

2. METHODS

At the Research Institute of Fiber Crops, research is being carried out to create a laboratory roller gin for ginning small samples of seed cotton [1, 2, 3]. A gin scheme has been developed, which is shown in Fig. 1.

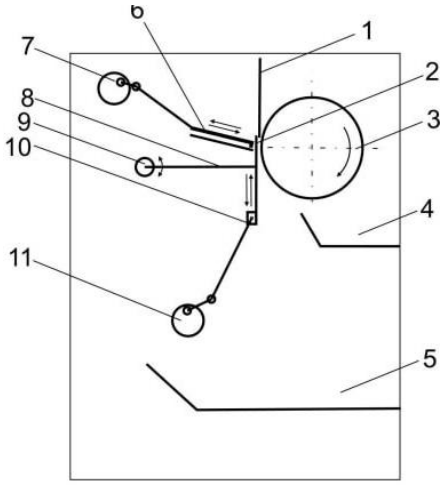


Figure 1. Diagram of the developed laboratory roller gin with a working roller and a two-knife system in the ginning zone

1 – stationary knife; 2 – movable knife; 3 – working roller; 4 – fiber chamber; 5 – seed chamber; 6 – cotton clamping mechanism; 7, 11 – cam shaft; 8 – grate; 9 – pulley; 10 – hinge for transmitting rotation.

The gin operates as follows. The working roller 3 performs rotational motion; the stationary knife 1 is pressed against its surface, and the movable (beating) knife 2 performs reciprocating motion along the stationary knife. The feeding and pressing mechanism 6 periodically moves along the grate 8 and delivers cotton particles to the ginning zone, while the cam shaft 7 compacts the cotton layer and partially aligns the fibers in parallel, which improves the conditions for their capture. The fibers caught by the roller surface are drawn under the stationary knife, while the seeds freed from the fiber pass through the grate into the seed chamber 5; the fiber is collected in chamber 4. Owing to this design, the gin does not require the formation of a seed-cotton roll and makes it possible to process samples weighing from 40–45 g.

The experimental prototype was manufactured according to working drawings at “Ijod” LLC. The working roller is made of textolite: discs 12 mm thick with an outer diameter of 60 mm and an inner diameter of 20 mm are assembled on an axle and clamped on both sides by flanges; the length of the roller together with the flanges is 210 mm; dead grooves are cut on the roller surface. The stationary knife is made of tool steel 3 mm thick. The grate is made of steel rods 4 mm in diameter with a base spacing of 7 mm between them. The roller material was chosen according to its coefficient of friction against the fiber: the RKM-2 material used on production gins (friction coefficient 0.6) is expensive, so textolite was adopted as an alternative for the laboratory gin, which does not require continuous operation.

The theoretical part of the work was carried out using the methods of theoretical and applied mechanics, the theory of mechanisms and machines, mathematical modeling of technological processes, and mathematical statistics. The movable knife performs harmonic oscillations along the roller surface: $\xi(t) = A\cdot\sin(\omega_k t + \phi_o)$, where A is the amplitude, ω_k is the angular frequency, and ϕ_o is the initial phase. The maximum velocity of the knife is equal to $A\omega_k$ and is reached when it passes through the middle position, while the maximum acceleration $A\omega_k^2$ is reached at the extreme positions. The oscillations of the knife cause a periodic change in the gap between its edge and the roller surface; the minimum design gap is denoted by δ_o, and the dimensionless parameter A/δ_o characterizes the relative amplitude. The mode of action of the knife on the flow of fiber tufts is determined by the frequency ratio $n = \omega_k/\omega_r$ (ω_r is the angular velocity of the roller): at integer values of n the system operates synchronously and provides uniform action on all sections of the roller, and the range n = 2…4 is considered rational.

The bond strength between the fiber and the seed consists of adhesive and mechanical components: $F_{bond} = F_{adh} + F_{mech}$. For fine-staple cotton varieties, the average detachment force of a single fiber is 0.8…1.5 cN, and its breaking load is 4…6 cN; from 8000 to 12000 fibers are attached to one seed, but in the real process they are separated successively, which substantially reduces the required force. Preserving the integrity of the fiber requires that the detaching force remain below its breaking load with a margin, which is taken into account by condition (8).

The experimental studies were carried out on the prototype gin. The product balance was determined on samples of seed cotton of the “Andijan-35” variety weighing 40, 60 and 80 g in three replications, by weighing the fiber and ginned seeds on an electronic balance. The influence of the dead-groove pitch on the quality of the ginning products was studied at pitches of 20, 40 and 60 mm (0.5 kg of cotton per variant; cotton moisture content 8.2%, trash content 1.32%, seed damage 0.6%), and the influence of the distance between the teeth of the seed comb at 6, 7 and 8 mm. The fiber and seed quality indicators were determined under laboratory conditions at the Research Institute of Fiber Crops. Ginning was considered sufficient at a residual seed fuzziness of not more than 9.0%. Production tests were carried out in the laboratory of an elite seed-growing farm in the Syrdarya region: the developed gin was compared with the existing ten-saw laboratory gin on seed cotton of the “Sultan” variety (15 kg of family samples for each variant; moisture content 8.7%, trash content 0.7%, seed damage 0.07%; three replications).

Let us consider the section of fiber clamped between the stationary knife and the ginning roller (Fig. 2).

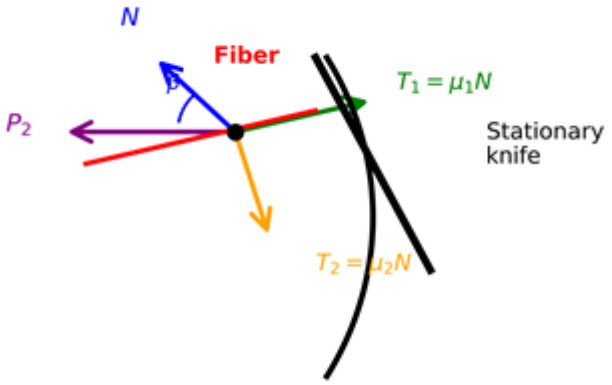


Figure 2. Diagram of the forces acting on the fiber in the contact zone of the stationary knife with the ginning roller

The following forces act on this section:

The force pressing the fiber against the roller from the side of the knife is the normal force N, directed perpendicular to the roller surface; it causes friction forces on the ginning roller ($T_1 = \mu_1 N \cos\beta$) and on the stationary knife: ($T_2 = \mu_2 N \cos\beta$,, where β is the angle between the direction of fiber tension and the normal to the roller surface). We also take into account the component of the pressing force acting along the direction of fiber tension:

$$P_2 = N \sin\beta.$$

The resultant force tending to detach the fiber from the seed is determined by the formula obtained in [4]:

$$P_0 = N(\mu_1 - \mu_2)\cos\beta + N\sin\beta.$$

For small angles $\beta(\beta \approx 0)$ this formula simplifies:

$$P_0 \approx N(\mu_1 - \mu_2). \qquad (1)$$

The friction coefficient of the fiber against the ginning roller μ_1 depends on the roller covering material and the condition of the fiber surface. For a leather roller working with fine-staple cotton, it was established experimentally [5] that $\mu_1 = 0.463$, and the friction coefficient against the knife surface μ_2 is determined by the knife material and its finish and is equal to $\mu_2 = 0.32$. Substituting these values into formula (1), we obtain:

$$P_0 = 0.143N. \qquad (2)$$

This relation shows that the detaching force amounts to about 14.3% of the normal pressing force.

The normal pressing force N depends on the elastic properties of the fiber and the geometric parameters of the system. According to the studies [6], the following relation can be used to estimate this force:

$$N = \frac{qbL}{\delta_0}, \qquad (3)$$

Where: q is the specific pressure per unit contact area; b is the width of the contact zone (knife length); L is the length of the fiber section in contact; δ_0 is the gap between the knife and the roller.

The specific pressure is related to the depth of indentation of the fiber into the roller surface. According to the Hertz formula modified for textile materials [6]:

$$q = \left[\frac{h}{\alpha}\right]^{1/0.75} = \frac{h^{4/3}}{\alpha^{4/3}}, \qquad (4)$$

Where: h is the indentation depth; α is a coefficient depending on the elastic properties of the materials ($\alpha = 415$ for a leather roller and cotton fiber).

The indentation depth, in turn, is related to the gap:

$$h \le (r_k)/2$$

where: r_k is the radius of curvature of the knife edge.

For typical values $r_k = 0.5\ mm$ we have h ≤ *0.25 mm. Substituting into formula (4), we obtain:*

$$q = \frac{(0.25)^{4/3}}{415^{4/3}} \approx 3.5 \cdot 10^{-6}\ \text{MPa}.$$

This is a very low pressure, which is explained by the elastic properties of the fiber. To obtain a sufficient detaching force, it is necessary to ensure a large contact length L or a small gap δ_0..

The introduction of a movable knife creates an additional dynamic component of the detaching force. The action of the movable knife is based on two effects.

When the movable knife moves away from the roller (in the phase of increasing gap), the fiber tufts are pushed aside, which increases the lever arm of the roller friction force relative to the point where the fiber is attached to the seed. This effect can be described by an additional moment:

$$\Delta M = F_{\text{fr.r}} \cdot \Delta L, \quad (5)$$

Where: $\Delta L = A\sin(\omega_k t)$ is the additional lever arm created by the displacement of the fiber tuft.

A periodic change in the force acting on the fiber leads to alternating stresses in the zone where the fiber is attached to the seed. This causes fatigue weakening of the bond, which can be taken into account through an effective weakening coefficient η_{fat}:

$$F_{\text{bond,eff}} = \eta_{\text{fat}} F_{\text{bond}},$$

where $\eta_{\text{fat}} < 1$ depends on the number of loading cycles and the amplitude of the pulsations.

The total detaching force in a system with a movable knife:

$$P_{\text{tot}}(t) = P_0 + P_{\text{add}}(t) = N(\mu_1 - \mu_2) + k_{\text{add}} A\omega_k^2 \sin(\omega_k t), \quad (6)$$

where k_{add} is a coefficient accounting for the influence of the knife oscillations on the detaching force.

It follows from formula (6) that the movable knife creates a periodic addition to the static force, and the amplitude of this addition is proportional to the square of the oscillation frequency and to the displacement amplitude.

For effective fiber separation, the maximum value of the detaching force must exceed the bond strength, taking weakening into account:

$$P_{\text{tot,max}} = P_0 + k_{\text{add}} A\omega_k^2 \geq \frac{F_{\text{bond}}}{\eta_{\text{fat}}}. \quad (7)$$

At the same time, the condition of non-damage to the fiber must be satisfied:

$$P_{\text{tot,max}} < \frac{F_{\text{br}}}{k_s}, \quad (8)$$

Combining conditions (7) and (8), we obtain the range of permissible values of the detaching force:

$$\frac{F_{\text{bond}}}{\eta_{\text{fat}}} \geq P_{\text{tot,max}} < \frac{F_{\text{br}}}{k_s}. \quad (9)$$

This inequality defines the permissible combinations of the parameters N, A, ω_k, ensuring high-quality ginning.

The force relations obtained make it possible to proceed to formulating the equations of motion of the system and developing a method for calculating the optimal parameters of the two-knife system.

Based on the force analysis carried out, we construct a mathematical model describing the dynamics of fiber separation from the seed under the action of the working elements of the two-knife system. This model makes it possible to calculate the trajectory of the fiber tuft, determine the separation time, and optimize the system parameters.

Let us consider the fiber tuft as a material point of mass m_{ft}, moving under the action of forces from the ginning roller, the knives, and resistance forces. Let us choose a coordinate system with the origin at the center of the roller, with the x axis directed tangent to the roller surface at the point of contact with the stationary knife.

The differential equation of motion of the fiber tuft projected onto the x axis:

$$m_{\text{ft}} \frac{d^2x}{dt^2} = F_{\text{fr.r}} - F_{\text{fr.k}} - F_{\text{aer}} - c\frac{dx}{dt}, \quad (10)$$

c is the damping coefficient, which accounts for internal friction in the fiber and energy dissipation during deformation.

Taking into account the relations obtained earlier:

$$F_{\text{fr.r}} = \mu_1 N(t),$$
$$F_{\text{fr.k}} = \mu_2 N(t),$$
$$F_{\text{aer}} = \frac{1}{2} c_x \rho S_{\text{mid}} v^2,$$

Where: N(t) is the normal pressing force, depending on the position of the movable knife; c_x is the aerodynamic drag coefficient; ρ is the air density; S_{mid} is the midsection area of the fiber tuft; $v = dx/dt$ is the velocity of the fiber tuft.

The normal pressing force varies owing to the oscillations of the movable knife:

$$N(t) = N_0 + \Delta N \sin(\omega_k t + \varphi_0),$$

where N_0 is the mean normal force; ΔN is the amplitude of the normal force pulsations.

Substituting these expressions into equation (10), we obtain:

$$m_{\text{ft}} \frac{d^2x}{dt^2} + c\frac{dx}{dt} + \frac{1}{2} c_x \rho S_{\text{mid}} \left(\frac{dx}{dt}\right)^2 = (\mu_1 - \mu_2)[N_0 + \Delta N \sin(\omega_k t + \varphi_0)]. \quad (11)$$

This is a nonlinear second-order differential equation with variable coefficients that describes the motion of the fiber tuft taking into account the pulsating load

from the movable knife.

At low velocities (v < 2 m/s), the quadratic aerodynamic drag term is small compared with the other forces and can be neglected. Let us introduce the effective damping coefficient:

$$c_{\text{eff}} = c + c_{\text{aer}},$$

where c_{aer} accounts for the linearized aerodynamic drag.

Linearized equation:

$$m_{\text{ft}} \frac{d^2x}{dt^2} + c_{\text{eff}} \frac{dx}{dt} = (\mu_1 - \mu_2)[N_0 + \Delta N \sin(\omega_{\text{k}} t + \varphi_0)]. \quad (12)$$

Divide both sides by m_{ft} and introduce the notation:

$$2\gamma = \frac{c_{\text{eff}}}{m_{\text{ft}}}, \quad F_0 = \frac{(\mu_1 - \mu_2)N_0}{m_{\text{ft}}}, \quad F_1 = \frac{(\mu_1 - \mu_2)\Delta N}{m_{\text{ft}}}.$$

Substituting the result into (13):

$$n = \frac{f_{\text{k}}}{f_{\text{r}}} = \frac{\omega_{\text{k}}}{\omega_{\text{r}}}, \quad (13)$$

Then equation (13) takes the form:

$$\frac{d^2x}{dt^2} + 2\gamma \frac{dx}{dt} = F_0 + F_1 \sin(\omega_{\text{k}} t + \varphi_0). \quad (14)$$

This is a non-homogeneous linear differential equation with constant coefficients.

The general solution of equation (14) consists of the solution of the homogeneous equation (free oscillations) and a particular solution of the non-homogeneous equation (forced oscillations).

$$\frac{d^2x_{\text{h}}}{dt^2} + 2\gamma \frac{dx_{\text{h}}}{dt} = 0.$$

Characteristic equation: $\lambda^2 + 2\gamma\lambda = 0$, roots: $\lambda_1 = 0, \lambda_2 = -2\gamma$. The general solution of the homogeneous equation:

$$x_{\text{h}} = C_1 + C_2 e^{-2\gamma t}. \quad (15)$$

We seek the particular solution of the non-homogeneous equation in the form:

$$x_{\text{p}} = A_0 t + B_1 \sin(\omega_{\text{k}} t + \varphi_0) + B_2 \cos(\omega_{\text{k}} t + \varphi_0).$$

Equating the coefficients of like functions, we obtain:

$$A_0 = F_0,$$

$$B_1 = \frac{F_1 \cdot 2\gamma\omega_{\text{k}}}{4\gamma^2\omega_{\text{k}}^2 + \omega_{\text{k}}^4}, \quad B_2 = -\frac{F_1\omega_{\text{k}}^2}{4\gamma^2\omega_{\text{k}}^2 + \omega_{\text{k}}^4}.$$

For small damping ($\gamma \ll \omega_{\text{k}}$) these coefficients simplify:

$$B_1 \approx \frac{2\gamma F_1}{\omega_{\text{k}}^3}, \quad B_2 \approx -\frac{F_1}{\omega_{\text{k}}^2}.$$

Amplitude of the forced oscillations:

$$B = \sqrt{B_1^2 + B_2^2} \approx \frac{F_1}{\omega_{\text{k}}^2}\sqrt{1 + \frac{4\gamma^2}{\omega_{\text{k}}^2}} \approx \frac{F_1}{\omega_{\text{k}}^2}. \quad (16)$$

Then the general solution can be written in the following form:

$$x(t) = C_1 + C_2 e^{-2\gamma t} + F_0 t + B \sin(\omega_{\text{k}} t + \varphi_0 + \psi), \quad (17)$$

where ψ is the phase shift, determined from the relation $\tan\psi = B_1/B_2$.

The constants C_1 and C_2 are determined from the initial conditions:

$$x(0) = 0, \quad \left.\frac{dx}{dt}\right|_{t=0} = 0.$$

From the first condition: $C_1 + C_2 + B\sin(\varphi_0 + \psi) = 0$.

From the second condition: $-2\gamma C_2 + F_0 + B\omega_{\text{k}}\cos(\varphi_0 + \psi) = 0$.

Solving this system, we find C_1 and C_2.

It can be seen from solution (17) that the motion of the fiber tuft consists of three components. The transient component $C_2 e^{-2\gamma t}$ decays rapidly with the characteristic time $\tau = 1/(2\gamma)$. For typical system parameters $\tau \approx 0.01 \ldots 0.05\ s$, which is much shorter than the residence time of the fiber tuft in the ginning zone. The steady uniform motion $F_0 t$ at a constant velocity

$$v_{\text{avg}} = F_0 = (\mu_1 - \mu_2)N_0/m_{\text{ft}}.$$

The oscillatory component $B\sin(\omega_{\text{k}} t + \varphi_0 + \psi)$ with an amplitude determined by formula (16).

3. RESULTS

Figure 3 shows the displacement of the fiber tuft for typical system parameters.

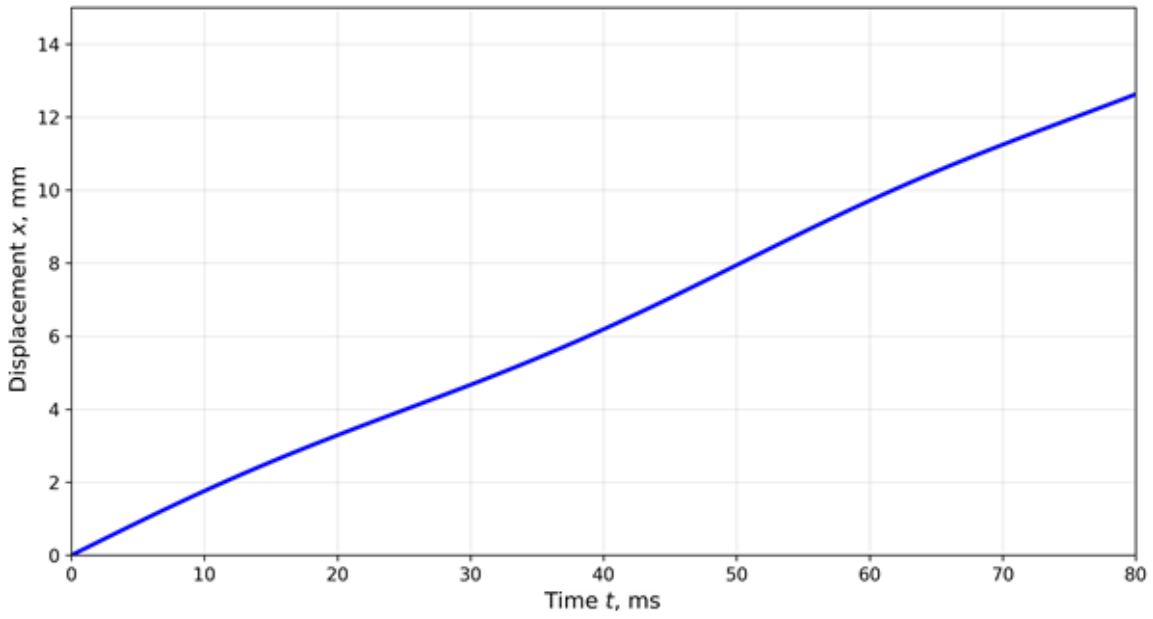


Figure 3. Time dependence of the fiber tuft displacement for the parameters: $N_0 = 5\ N, \Delta N = 2\ N, \omega_k = 125\ rad/s, m_{ft} = 4.5\ g$

The graph in Fig. 3 shows that after a short transient process the fiber tuft moves with an increasing average velocity, on which high-frequency oscillations caused by the pulsation of the force from the movable knife are superimposed. These oscillations contribute to fatigue weakening of the bond between the fiber and the seed.

The fiber separates from the seed at the moment when the displacement of the fiber tuft reaches the critical value x_{cr}, at which the tension in the zone where the fiber is attached to the seed exceeds the bond strength:

$$T(x_{cr}) = F_{bond}/\eta_{fat},$$

where η_{fat} is the bond weakening coefficient due to cyclic loading.

The fiber tension is related to the displacement through Hooke's law:

$$T = E_r S_r \frac{x}{L_r},$$

where E_r is the elastic modulus of the fiber; S_r is the cross-sectional area of the fiber; L_r is the fiber length.

Critical displacement:

$$x_{cr} = \frac{F_{bond} L_r}{\eta_{fat} E_r S_r}. \quad (18)$$

The separation time t_{sep} is found from the condition $x(t_{sep}) = x_{cr}$. When uniform motion predominates, $(F_0 t \gg B)$:

$$t_{sep} \approx \frac{x_{cr}}{F_0} = \frac{m_{ft} F_{bond} L_r}{(\mu_1 - \mu_2) N_0 \eta_{fat} E_r S_r}. \quad (19)$$

Expression (19) shows that the separation time is inversely proportional to the normal pressing force and to the difference between the friction coefficients, and directly proportional to the mass of the fiber tuft and the bond strength between the fiber and the seed. The developed mathematical model makes it possible to proceed to solving the optimization problem, that is, to determining the values of the design and operating parameters at which the maximum productivity of the gin is achieved while ensuring the required quality of cotton processing.

The performance of a roller gin is determined by a set of technological and technical-economic indicators. As the main optimality criteria we take the fiber productivity $\Pi(kg/h)$, the cleaning effect E_{cl} (%), the fiber damage coefficient, and the energy intensity of the process.

The complex optimality criterion can be formulated as:

$$\Phi = \frac{\Pi \cdot E_{cl} \cdot (1 - K_{dmg})}{E_{sp}} \to max, \quad (20)$$

The productivity of a roller gin is determined by the number of fiber tufts that can be processed per unit time and by the mass of fiber separated from one tuft. According to [5, 6, 7], the productivity can be represented as the sum of two components:

$$\Pi = \Pi_1 + \Pi_2, \quad (21)$$

where : Π_1 is the productivity due to fiber detachment by the beater roller and the work of the friction forces

of the ginning roller:

$$\Pi_1 = \kappa_1 \frac{0.06 n_o P}{f_1 N_1 [l+(M l_1 + s_1)]}, \quad (22)$$

Π_2 is the productivity due to the work of the detaching forces under the action of the movable knife:

$$\Pi_2 = \kappa_2 \frac{3.6 q b L (\mu_1 - \mu_2) v_{dr}}{(M l_1 + s_1) f_1 N_1}. \quad (23)$$

Here: n_o is the number of knife stroke cycles; P is the impact force; N_1 is the number of fibers in 1 g of fiber; l is the length of the ginning roller; $M l_1$ is the mathematical expectation of the fiber length on the fiber tuft; s_1 is the empirical standard deviation of the fiber length on the fiber tuft; f_1 is the strength of fiber attachment to the seeds; κ_1, κ_2 are the nonuniformity coefficients; q is the specific pressure per unit contact area; b is the width of the contact zone; L is the length of the fiber section in contact; v_{dr} is the fiber draw-in speed.

In a classical single-knife system, the component Π_2 is determined only by the static detaching force. In the proposed two-knife system, owing to the oscillations of the movable knife, this component increases. Let us introduce the intensification coefficient λ, which accounts for the contribution of the dynamic action:

$$\Pi_{22k} = \lambda \Pi_{2h}, \quad (24)$$

where Π_{2h} is the productivity of the single-knife system, Π_{22k} is the productivity of the two-knife system.

The intensification coefficient depends on the oscillation parameters of the movable knife and on the operating mode of the gin. On the basis of the theoretical studies and experimental verification carried out, the following dependence was obtained:

$$\lambda = 1 + \alpha_{int} \left(\frac{A}{\delta_0}\right) \sqrt{\frac{\omega_k}{\omega_r}}, \quad (25)$$

where $\alpha_{int} = 0.15 \ldots 0.25$ is a coefficient depending on the properties of the cotton; A/δ_0 is the relative oscillation amplitude; ω_k/ω_r is the frequency ratio.

At the optimal parameters ($A/\delta_0 \approx 2, \omega_k/\omega_r \approx 3$) the intensification coefficient is:

$$\lambda \approx 1 + 0.20 \times 2 \times \sqrt{3} \approx 1.69.$$

This means that the productivity due to the second component increases by approximately 69% compared with the classical single-knife system.

Total productivity of the two-knife system:

$$\Pi_{2k} = \Pi_1 + \lambda \Pi_2. \quad (26)$$

Figure 4 shows the dependence of the relative productivity increase on the parameters of the movable knife.

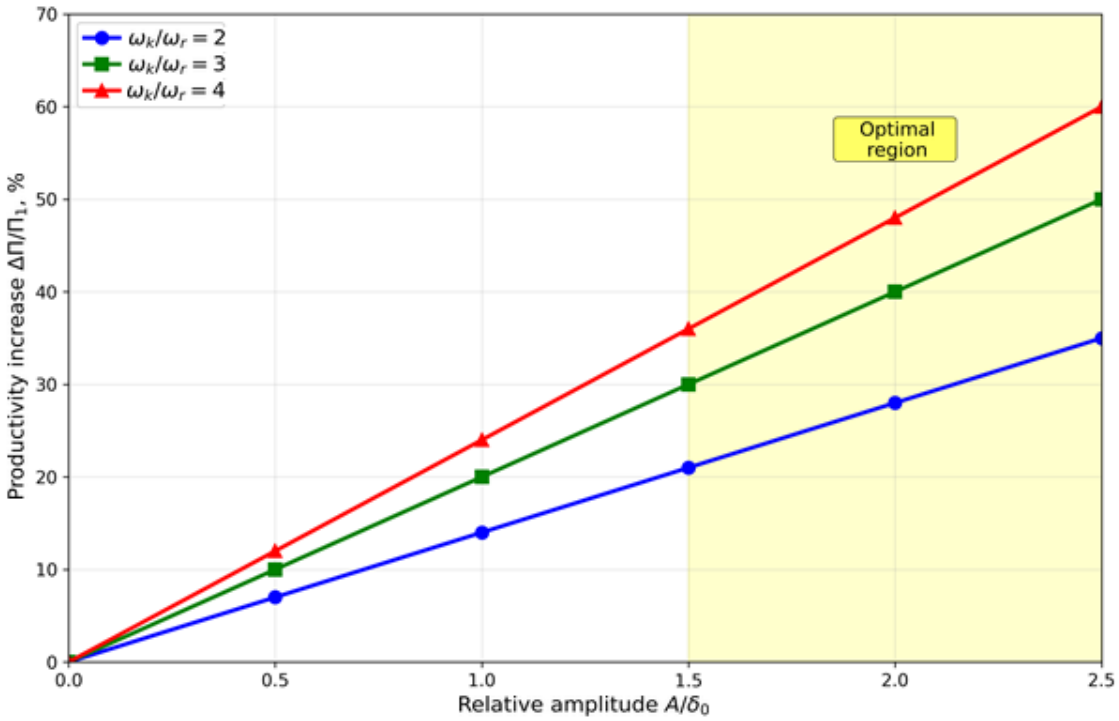


Figure 4. Dependence of the relative productivity increase on the relative oscillation amplitude of the movable knife at various frequency ratios

It can be seen from the graph in Fig. 4 that the maximum effect is achieved at $A/\delta_0 = 2.0 \ldots 2.5$ and $\omega_k/\omega_r = 3 \ldots 4$. A further increase of these parameters is inexpedient because of the increased risk of fiber damage.

Solving the optimization problem by criterion (20), with constraints on the minimum gap, relative amplitude, frequency ratio, cleaning effect and fiber damage (not more than 2%), showed that the rational values are a minimum gap δ_o = 2.0 mm, a relative amplitude $A/\delta_o \approx$ 2…2.5 and a frequency ratio ω_k/ω_r = 3…4. Combinations of parameters at which fiber damage exceeds 2% or the productivity increases insufficiently lie outside the region of permissible values. The introduction of the movable knife raises the cleaning effect of the gin by 13–14% compared with the single-knife system owing to the increased multiplicity of action on the fiber and the fatigue weakening of the bond between the fiber and the seed.

Analysis of the dynamic coefficient showed that it increases sharply when the knife oscillation frequency coincides with the natural frequency of the "fiber – seed" system; however, at a roller rotation speed of 180…220 rpm, achieving resonance would require a frequency ratio n ≈ 20…30, which is technically difficult to implement. Therefore, the pre-resonance region (n_{res} < 0.5) was considered rational, in which the dynamic coefficient is close to unity and dangerous overloading of the fiber is excluded.

It was established experimentally that the friction coefficient of the roughened surface of the textolite roller against cotton fiber is 0.45, and that periodic wiping of the surface with ethyl alcohol can raise it to 0.6, that is, to the level of the RKM-2 material. When cleaned samples weighing 40, 60 and 80 g were ginned, the fiber yield was 43.26–43.55% and the yield of ginned seeds was 53.6–55.16%; the process ran stably at all sample weights (Table 1). The high fiber yield is explained by the fact that samples cleaned of trash impurities were used.

Table 1. Yield of fiber and ginned seeds when ginning samples of seed cotton (mean values over three replications)

Sample mass, g	Fiber, g (%)	Ginned seeds, g (%)
40.0	17.31 (43.27)	21.44 (53.60)
60.0	25.96 (43.26)	32.59 (54.31)
80.0	34.84 (43.55)	44.13 (55.16)

The dead-groove pitch has a significant effect on the quality of the ginning products (Table 2). The lowest values of fiber trash content (3.91%) and mechanical seed damage (6.4%) were obtained at a pitch of 40 mm; at pitches of 20 and 60 mm the trash content was 4.41 and 4.32%, and the seed damage 7.8 and 6.9%, respectively. The residual fiber content of the seeds practically did not change (0.020…0.027%). A groove pitch of 40 mm was adopted for the developed gin.

Table 2. Influence of the dead-groove pitch of the working roller on the quality of fiber and seeds

Indicator	20 mm pitch	40 mm pitch	60 mm pitch
Share of trash impurities in the fiber after ginning, %	4.41	3.91	4.32
Mechanical damage of seeds after ginning, %	7.8	6.4	6.9
Residual fiber content of seeds, %	0.021	0.020	0.027

The distance between the teeth of the seed comb determines the completeness of ginning (Table 3). At 6 and 7 mm the process ran stably: the share of under-ginned seeds and seeds with fiber tufts was 2.37 and 3.53%. At 8 mm it rose to 13.67%, because the gap exceeded the geometric dimensions of well-ginned

seeds. A distance of 6 mm is recommended for small-seeded varieties, and 7 mm for medium- and large-seeded ones.

Table 3. Influence of the distance between the teeth of the seed comb on the quality of ginned seeds

Distance between teeth, mm	Ginned to fuzziness not exceeding 9.0%, %	Fuzziness 9.0–11.0%, %	Under-ginned seeds and seeds with fiber tufts, %
6.0	72.60	25.03	2.37
7.0	67.87	28.60	3.53
8.0	49.27	37.06	13.67

Comparative production tests (Table 4) showed that, at the same productivity (60 kg/h), by reducing the machine cleaning time after each sample from 6 to 3 min, the developed gin increases the fiber yield from 38.0 to 38.7%, reduces the increase in mechanical seed damage from 1.3 to 0.4%, and reduces the installed power from 3 to 0.7 kW. The calculated economic effect when processing 250 samples of 15 kg each (3750 kg of raw cotton) is about 181.6 million soums per farm, of which the main part (170.34 million soums) comes from the reduction in seed damage, which increases field germination.

Table 4. Results of comparative tests of the developed roller gin and the existing ten-saw laboratory gin

Indicator	Existing ten-saw gin	Developed roller gin
Sample mass, kg	15	15
Ginning time of one sample, min	9	12
Gin cleaning time after a sample, min	6	3
Total processing time of a sample, min	15	15
Productivity, kg/h	60	60
Mass of fiber obtained, kg	5.7	5.805
Fiber yield, %	38.0	38.7
Increase in mechanical damage of seeds, %	1.3	0.4
Installed power, kW	3	0.7

4. DISCUSSION

The results obtained are consistent with modern views on the role of frictional and dynamic factors in roller ginning. Formula (1) corresponds to the fiber detachment condition obtained in [8]: the pulling force is determined by the product of the normal force and the difference between the friction coefficients, and for the efficient operation of the "roller – knife" pair one should strive for the maximum μ_1 and the minimum μ_2. The small value of the static detaching force (14.3% of N) explains why [8] proposed a periodic change of the load in the contact zone of the knife with the drum in order to intensify the process; in the proposed gin this idea is implemented in the form of oscillations of the movable knife, for which the design relations (6)–(9) were obtained.

The conclusion that periodic loading facilitates fiber separation is supported in [11]: the fibers are separated successively, and a mode close to resonance reduces the impact impulse and seed damage. At the same time, [11] notes that the dynamic "fiber – seed" system may enter a region of parametric resonance, where the motion is unstable; therefore, limiting the frequency ratio to the range $\omega_k/\omega_r = 3…4$ and choosing the pre-resonance region ($n_{res} < 0.5$) are justified from the standpoint of the safe operation of the two-knife system.

The reduction of the increase in mechanical seed

damage to 0.4% is especially important for seed production, since seed damage in gins is associated with the density and rotation speed of the seed-cotton roll [13, 14], whereas in the proposed gin the samples are processed in small portions without forming a seed-cotton roll. The advantages of the roller method in terms of fiber indicators are consistent with the results of comparative studies [10], and the preservation of fiber quality during ginning, according to [14], is determined by the absence of machine overload and by keeping the cotton moisture content within 5–8%. The durability of the dead grooves of the working drum of a roller gin is considered in [14]; for the textolite roller of the developed gin, the wear resistance of the grooves requires separate study.

The limitations of the model should be taken into account: the fiber tuft is treated as a material point, the equation of motion is linearized (velocities below 2 m/s), the friction coefficients are taken to be constant, and the fatigue weakening of the bond is accounted for by the coefficient $\eta_{fat} < 1$. The intensification coefficient (25) was obtained from a limited number of experiments, so for other varieties and cotton moisture contents its values require experimental refinement. In further research it is advisable to measure the bond strength between the fiber and the seed and the trajectory of the fiber tuft directly (in particular, by high-speed filming), and also to determine the wear of the textolite roller during long-term operation.

5. CONCLUSION

Based on the force analysis carried out, a mathematical model was constructed that describes the dynamics of fiber separation from the seed under the action of the working elements of the two-knife system. This model makes it possible to calculate the trajectory of the fiber tuft, determine the separation time, and optimize the system parameters.

In a classical single-knife system, the productivity component is determined only by the static detaching force. In the proposed two-knife system, owing to the oscillations of the movable knife, this component increases.

On the basis of the theoretical studies and experimental verification carried out, a dependence for the intensification of the cotton ginning process in a roller gin was obtained. It was found that the intensification coefficient depends on the oscillation parameters of the movable knife and on the operating mode of the roller gin.

It was established that, at friction coefficients $\mu_1 = 0.463$ and $\mu_2 = 0.32$, the static detaching force of the stationary knife amounts to only 14.3% of the normal pressing force; therefore, the decisive role is played by the dynamic component from the oscillations of the movable knife: it is proportional to the amplitude and the square of the oscillation frequency and, together with the fatigue weakening of the bond, ensures fiber separation without exceeding its breaking load.

The fiber separation time is inversely proportional to the normal pressing force and to the difference between the friction coefficients, and directly proportional to the mass of the fiber tuft and the strength of its bond with the seed. The rational parameters of the two-knife system are: minimum gap $\delta_o = 2.0$ mm, relative amplitude $A/\delta_o \approx 2…2.5$, and frequency ratio $\omega_k/\omega_r = 3…4$ in the pre-resonance region; in this case the cleaning effect increases by 13–14%.

The dead-groove pitch of the textolite roller (40 mm) and the distance between the teeth of the seed comb (6 mm for small-seeded and 7 mm for medium- and large-seeded varieties) were substantiated experimentally. Compared with the existing ten-saw laboratory gin, at the same productivity (60 kg/h) the fiber yield increases by 0.7% (from 38.0 to 38.7%), the increase in mechanical seed damage decreases from 1.3 to 0.4%, and the installed power decreases from 3 to 0.7 kW.

Further research should be directed at the direct measurement of the bond strength between the fiber and the seed and of the dynamics of the fiber tuft, at refining the intensification coefficient for different varieties and cotton moisture contents, and at studying the wear resistance of the working roller.

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