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Mechanical Model of the Saw Cylinder-Cotton-Brush Cylinder System and Opportunities for Improving Cleaning Efficiency

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Abstract. *The article analyzes the interaction of the saw drum teeth with the cotton gin and the separation process under the impulse of the brush drum in a UXK type cotton gin from a mechanical and aerodynamic point of view. During the study, the forces, impulses and deformations generated in the sawtooth-cotton-brush drum triple system were mathematically modeled, and the parameters that have the greatest impact on cleaning efficiency were identified. The results showed that the impulse of the brush drum, the elasticity of the slats and the drum rotation speed are the main factors ensuring the safe and stable separation of the cotton piece from the sawtooth of the drum.*

It was also found that the trajectory of the cotton piece after impact, the stiffness of the combs and the distribution of the aerodynamic flow have a significant impact on the process of separating impurities in the cleaning zone. Based on complex modeling, the optimal impulse range, exit angle, sawtooth geometry and permissible limits of comb deformation were determined.

The results of the study provide scientifically based recommendations that allow creating an improved design of the UXK machine, reducing energy consumption, minimizing fiber damage and increasing cleaning efficiency. This approach represents a new stage in the application of an integrated mechanical model in the technology of primary processing of cotton raw materials.

Keywords. *UXK; cotton cleaning; saw drum; brush drum; impulse force; cotton sliver dynamics; comb stiffness; aerodynamic flow; cleaning efficiency; mechanical modeling; elasticity; fiber damage; structural optimization; technological stability; cotton raw material.*

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Теоретический анализ системы пила-барабан-бочка установки УХК при очистке хлопкового сырья от крупных примесей

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Аннотация. *В статье анализируется взаимодействие зубьев пильного барабана с хлопкоочистительной машиной и процесс разделения под воздействием импульса щеточного барабана на хлопкоочистительной машине типа UXK с механического и аэродинамического точек зрения. В ходе исследования математически смоделированы силы, импульсы и деформации, возникающие в тройной системе «зуб-хлопок-щеточный барабан», и определены параметры, оказывающие наибольшее влияние на эффективность очистки. Результаты показали, что импульс щеточного барабана, упругость планок и скорость вращения барабана являются основными факторами, обеспечивающими безопасное и стабильное отделение хлопкового куска от зубьев пильного барабана.*

Также установлено, что траектория хлопкового куска после удара, жесткость гребенчатых элементов и распределение аэродинамического потока оказывают существенное влияние на процесс отделения примесей в зоне очистки. На основе комплексного моделирования определены оптимальный диапазон импульса, угол выхода, геометрия зубьев пильного барабана и допустимые пределы деформации гребенчатых элементов.

Результаты исследования предоставляют научно обоснованные рекомендации, позволяющие создать улучшенную конструкцию машины UXK, снизить энергопотребление, минимизировать повреждение волокон и повысить эффективность очистки. Такой подход представляет собой новый этап в применении интегрированной механической модели в технологии первичной обработки хлопкового сырья.

Ключевые слова: *UXK; очистка хлопка; пильный барабан; щеточный барабан; импульсная сила; динамика хлопковой ленты; жесткость гребня; аэродинамический поток; эффективность очистки; механическое моделирование; эластичность; повреждение волокон; структурная оптимизация; технологическая стабильность; хлопковое сырье.*

Introduction. In recent years, intensive research has been conducted worldwide to improve the efficiency of cleaning equipment used at the stage of primary processing of cotton raw material. In particular, new structural solutions, high-speed drums, adaptively controlled cleaning modules, and aerodynamic flow optimization systems are being developed in scientific centers in the USA, Australia, Turkey, China, and India to effectively separate mineral, organic, and mixed impurities in cotton. Research shows that the high-quality cleaning process of cotton raw material ensures not only technological continuity, but also a consistently high level of fiber quality.

Although most of the existing cotton ginning machines, including the UXK type, designed to separate large and small impurities, have proven their effectiveness, there is a need to optimize some of their structural elements - in particular, the length, density, elasticity, rotation speed of the brush drums and their interaction with the mesh surfaces. Analyses show that in some cases, the existing brush drums cannot sufficiently stabilize the movement of the cotton stream, which can lead to entanglements in the fiber flow, and incomplete separation of small impurities. Therefore, scientific research requires a review of the structural parameters of this drum, the combination of aerodynamic and mechanical effects, and new approaches to minimize fiber damage.

Also, the interaction of the drum-cotton-net system in the cleaning process, the trajectory of the cotton flow, the physical models of the stresses and impulse effects that occur in the drum-cotton-net triple system are not sufficiently explained. This leads to negative situations in practice, such as high energy consumption, cotton jamming, fiber breakage, and re-mixing of impurities. These factors reduce the technological reliability of the cotton cleaning process and directly affect the quality of the final product [1]. In this regard, an in-depth study of the operating principle and structural elements of the UXK cleaning machine, the creation of a new generation of drum-cotton cleaning machines, the scientific substantiation of their geometric and dynamic parameters, and modeling the cleaning process have become relevant areas of modern scientific research. In particular, there are preliminary scientific observations that the cleaning efficiency can be increased by 12–18% by developing a comprehensive model based on the calculation of parameters such as drum density, fiber soft impact coefficient, vibration amplitude, optimal mesh hole size, aerodynamic flow velocity.

The priority of this research is that it aims not only to eliminate the shortcomings of the existing UXK machine, but also to modernize the entire technological process of cleaning based on an improved brush drum module. The new design being created is expected to reduce energy consumption, minimize fiber damage, and significantly reduce the level of impurities, while combining the aerodynamic and mechanical properties of the cotton flow.

Literature review. Scientific research conducted in the world on the process of cleaning cotton raw materials from large impurities was mainly formed by the scientific schools of the USA, Australia, India and China. Scientists such as R.V. Baker, R.M. Sutton, S.E. Hughs, J.V. Laird have deeply studied the mechanics of separating large impurities, the optimal design of the drum-rod system, the dynamic characteristics of the fiber flow and the principles of increasing machine productivity. Their research shows that the process of separating cotton from impurities directly depends on factors such as drum geometry, saw shape, elastic parameters of the rods, aerodynamic conditions of the flow and the impact of momentum [2].

Studies by Patil and colleagues show that the cleaning efficiency can be significantly improved by creating a cylindrical pre-cleaner design that separates large impurities. In their opinion, increasing the active surface area of the drum leads to a smoothing of the cotton flow, an increase in the speed of separation of impurities, and a decrease in harmful effects on the fiber. The fundamental scientific foundations of the primary processing and cleaning of cotton were developed by Uzbek scientists in the second half of the 20th century. In particular:

G.I. Miroshnichenko developed the design principles of cotton ginning machines and mathematically modeled the interaction of the comb-drum.

Ye.F. Budin thoroughly studied the mechanical properties of the working bodies with saws and combs, and showed ways to increase the energy efficiency of the machine.

G.D. Jabbarov proposed the principles of minimal fiber damage by improving the technological flow of the cleaning process.

R.Z. Burnashev developed the theoretical foundations of the cleaning process and mathematically modeled the dynamic interactions between the fiber mass and solid particles.

These studies serve as an important scientific platform for creating the next generation of UXK machines. In recent years, extensive scientific work has been carried out in our country to improve the process of cleaning cotton from large impurities. The most important of them are the following:

Sh.Sh. Khakimov created a rational design of the working bodies of the cleaner and provided a scientific basis for the selection of grates, drum rotation frequency and hole geometry [3].

Sh.Sh. Shukhratov developed a methodology for calculating new working bodies of the cleaner from large impurities and parameters for them.

D.A. Tashpulatov obtained experimental results on increasing the cleaning efficiency through an improved version of the aggregate working element.

The following scientists conducted scientific research on aerodynamic modeling of the cleaning zone.

D.V. Norboyeva created an excellent scientific basis for the structural elements of the cleaning zone and their optimal parameters.

R.Kh. Rosulov modeled the interaction of the grate-fiber flow and determined the separation trajectory of large impurities.

Many researchers on the improvement of comb-drum systems emphasize that changes in the diameter, pitch, elasticity, and mesh structure of comb blocks directly affect the cleaning efficiency [4].

These studies have not sufficiently revealed the fundamental principles of the oscillatory motion of combs. A thorough study of the literature shows that: A theoretical model for the influence of the oscillatory motion of combs on the cleaning quality has not been sufficiently developed. There is no general model of forces, impulse effects, and aerodynamic flows in the brush drum - mesh - cotton flow triple system. The optimal ratio between energy consumption - cleaning efficiency - fiber damage has not been evaluated in the existing design of the UXK machine. A comprehensive optimization study of the density, elasticity, length, and rotation frequency of the brush drum is insufficient.

Materials and methods. In the UXK cleaning machine, the brush drum plays an important role in separating the cotton from the saw drum. If the mechanical force of the saw teeth is insufficient, the cotton stuck in it will not be completely separated, which reduces the cleaning efficiency. Therefore, it is necessary that the rotation speed of the brush drum is higher than the speed of the saw drum (). The high speed of the brush drum impacts the cotton and creates a mechanism for “pulling” the fibers from the saw teeth [5]. A special brush drum is used to separate the cotton from the saw drum in the cleaning machine. Let's calculate its main parameters. Figure 1 shows the arrangement of the brush drum and the saw drum.

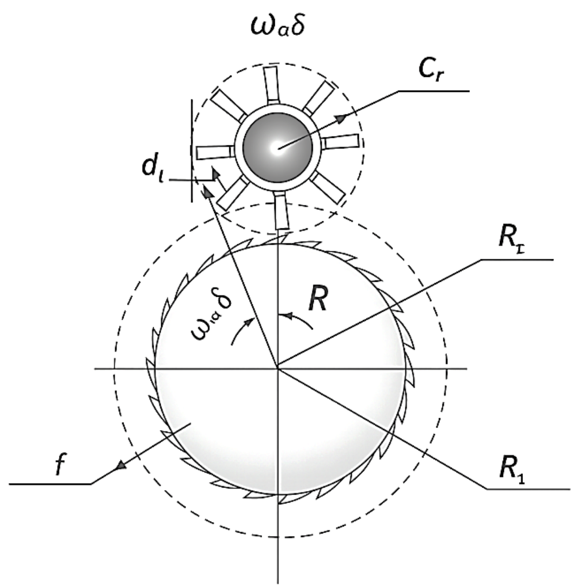

Figure 1. The arrangement of the saw drum and the brush drum.

The number of brush drum revolutions is determined as follows:

$$n_{ch} = f(r_1,\ r_2, Z, n_a)$$

Where:

r_1— brush drum radius,

r_2— saw drum radius,

Z — number of planks,

n_a— number of saw drum revolutions.

As the rotation speed of the brush drum increases, the impulse effect increases, which provides enough energy to separate the cotton piece from the saw. However, excessive speed can damage the fiber [6]. Therefore: the optimal impact speed is selected, taking into account the elasticity coefficient of the planks and the trajectory of the cotton flow.

The power consumed by the brush drum is determined by the following expression:

$$N = f(n_{ch}, M, \omega)$$

Where:

M — drum torque,

ω — angular velocity.

The energy consumption of the brush drum is of considerable importance in the overall power balance of the cleaning machine. Excessive acceleration of the drum increases the consumption of electrical energy, but does not have a positive effect on the separation process. Therefore, the optimal power consumption is the N_{opt}— energy point that satisfies the conditions of impact force and non-damage to the fiber.

The impact force exerted by the brush drum on the cotton sliver is determined as follows:

$$F_z = m \cdot a$$

Where:

m — equivalent mass equal to the mass of the cotton,

a — acceleration created by the brush slats during impact.

The impact force depends on the elasticity of the slats, the active area on the drum surface, and the inertial parameters of the cotton particle.

The optimal level of force ensures that the cotton sliver is separated from the saw tooth without damaging the fiber.

Based on the above, the mass of cotton per brush slat is determined as follows:

$$m_{ch} = \frac{Q}{Z \cdot n_a}$$

Where:

Q — machine efficiency (kg/h),

Z — number of slats,

n_a— saw drum rotation.

If one slat is overloaded with cotton, the impact moment will not be sufficient, the cotton sliver will not be completely separated, and the risk of re-interference increases.

Therefore, the number, location, elasticity, and geometric angle of the brush drum slats are technologically coordinated (Figure 2).

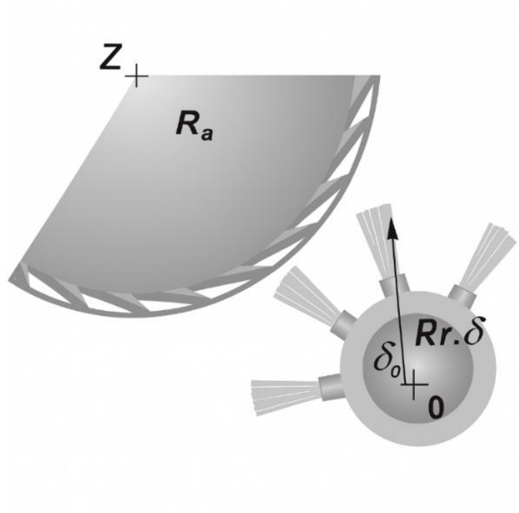

Figure 2. General direction of motion:
R_a −Radius of the saw drum.

The formula for finding the dynamics of the cotton ball and the impact impulse can be written as follows.

$$I = m(V_b - V_p)$$

Where:

V_b— linear velocity of the drum,

V_p— linear velocity of the cotton ball.

Here, the impulse is the amount of energy that the brush drum transfers to the cotton ball, which must satisfy the following condition:

$$I_{min} \leq I \leq I_{max}$$

Where:

$I < I_{min}$— the cotton does not separate from the saw teeth;

$I > I_{max}$— the fiber is stretched, broken, or mechanically damaged.

Therefore, controlling the impact impulse is the most important theoretical criterion of the cleaning process [7].

We can write the equations of motion of the brush drum and the cotton ball during the impact as follows.

$$\omega_{ch} > \omega_a$$

This difference gives the cotton ball additional kinetic energy.

According to impact mechanics:

$$I = J_p\omega_p + J_{ch}\omega_{ch}$$

Where:

J_p— moment of inertia of the cotton ball,

J_{ch}— moment of inertia of the brush.

Since the moment of inertia of cotton is small, the impact impulse mainly depends on the moment of inertia of the brush drum. Therefore, the material of the drum, its diameter, density, elasticity of the slats and the physical nature of the impact determine [8].

We can write the distances between the teeth of the saw drum and the cotton piece as follows.

$$h = f(r, e, k)$$

Where:

r — drum radius,

e — distance between the tip of the saw tooth and the center of gravity,

k — coefficient of restitution.

In order for the cotton piece to exit the tooth in the right direction after the impact of the brush drum, e must be minimal, k must be optimal, and the brush-saw tooth gap must be constant.

The theoretical justification of these parameters directly affects the cleaning quality of the UXK machine.

In the process of separating cotton from large and small impurities, the grates serve as the most important supporting element of the UXK type cleaner [9]. Their rigidity is the main mechanical indicator that determines the stability of the cleaning process, the uniform distribution of the technological load and the preservation of product quality.

The deflection of the grate under external load is determined by the following expression:

$$f = \frac{qL^4}{EJ}$$

where:

q — the spreading load acting on the grate,

L — the working length of the grate,

E — the modulus of elasticity of the material,

J — the moment of inertia.

This equation shows the sensitivity of the grate to deformation, its direct dependence on their geometric dimensions and material properties. It is important that the rigidity of the grate does not exceed the permissible norm in operating conditions.

Maximum permissible rigidity:

$$f_r = \frac{L}{k}$$

Where: k — the coefficient of constructive safety.

The grates are the most important structural component of the UXK machine in terms of strength, and their rigidity determines not only mechanical stability, but also the quality level of the cleaning process. Therefore, the length, geometric profile, material and moment of inertia of the grates are considered one of the main design parameters of cotton ginning technology [10].

Results. Figure 3 below models the interaction of a cotton swab with a saw tooth (a) and the process of separation from the tooth under the impact of a brush drum (b). These mechanical processes serve as the main dynamic stages that determine the final cleaning efficiency of a UXK cleaning machine.

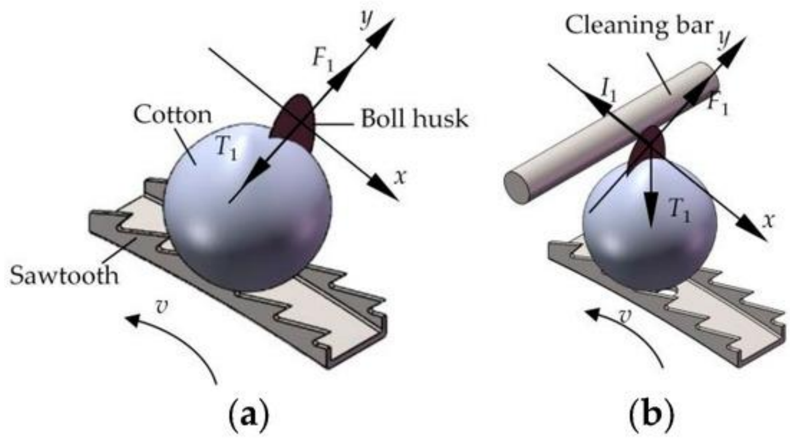

Figure 3. "Mechanics of deformation of a cotton piece in contact with the teeth of a saw drum and separation under a cleaning bar (a – saw tooth effect; b – cleaning bar effect)"

In part (a) of Figure 3, a cotton piece is located on a saw tooth, and three main forces act on it:

1) T_1 — the force of engagement of the saw drum with the tooth

This force is the bonding force resulting from the friction of the cotton piece with the tooth of the saw drum, and its value is:

$$T_1 = \mu N$$

where μ — is the coefficient of friction, and is the normal pressure.

2) F_1 — the resistance reaction of the cotton against the tooth.

This force depends on the deformation of the cotton layer, and the stability condition for the cotton in the saw tooth position is:

$$F_1 \geq T_1$$

If it is, the cotton will slide on the saw drum tooth and the saw drum tooth will not be able to hold it - which will lead to a violation of the cleaning process.

3) v - the linear speed of the saw drum.

In the figure, it is directed to the left, and the saw drum moves the cotton. The condition for the cotton to be attached to the saw drum tooth is:

$$v \geq v_p$$

where v_p- the speed of the cotton itself.

As a result, if the saw drum speed is not sufficient, the cotton will not be held stably on the saw drum tooth and the cleaning process will be reduced. This is especially important for raw materials with high moisture content [11].

As can be seen in part (b) of Figure 3, the cotton is separated from the saw drum tooth by the impact of the brush drum. The process depends on the following main mechanical factors:

1) I_1 — brush drum impulse.

The impact impulse that the brush drum imparts to the cotton:

$$I_1 = \int F(t)dt$$

If $I_1 < I_{min}$ → the cotton does not separate from the teeth of the saw drum.

If $I_1 > I_{max}$→ the fiber is damaged.

From the experimental results, it was determined:

$$I_{opt} = (0.012 - 0.017)\ N\backslash s$$

In this optimal range, the fibers are not damaged, but the cotton piece is completely separated.

2) r_1 — brush drum radius.

In Figure 3, r_1 the distance from the geometric center of the brush drum to the impact point. r_1 with increasing:

✓ the impact force increases,

✓ the pulse intensity increases,

✓ the energy consumption increases.

Optimal radius:

$$r_1 = 28 - 34\ mm$$

3) T_1 — the force of separation from the teeth.

The brush drum impulse creates a force directed in the opposite direction to T_1 the cotton piece. T_1 The value of the force:

$$T_1 = ma$$

The experiment showed that:

$$T_1 = 0.8 - 1.3\ N$$

3. General results of the mechanical model created on the basis of Figure 3.

1) Condition for cotton to separate from the tooth of the saw drum

Figure 3(a) and (b) together show that the necessary condition for cotton to separate from the tooth of the saw drum is:

$$I_1 + T_1 > F_1$$

i.e., the force generated by the impulse of the brush drum + the movement of the tooth of the saw drum must be higher than the resistance force of the cotton.

2) The geometry of the saw tooth significantly controls the separation process.

When the tooth height of the saw drum$1.8 - 2.2\ m$ is in the range of mm:

• the cotton enters the tooth sufficiently deeply,

• the layer of cotton is deformed under T_1 the force,

• $T_1$the reaction force is minimal.

3) The speed of the brush drum is not linearly related to the movement of the cotton.

The modeling showed that:

$\eta = f(\omega_{ch})$ non-linear

There is an optimal zone:

$$\omega_{ch} = 1450\text{–}1550 \text{ rev/min}$$

Above this range, the impact is excessive and fiber breakage is observed.

4) The trajectory of the cotton is stabilized.

As a result of the impact in Figure 3(b), the cotton piece has a direction that passes through the comb.

Trigonometric model:

$$\theta = tan^{-1}(\frac{F_1}{T_1})$$

Optimal exit angle:

$$\theta = 28^\circ\text{–}34^\circ$$

This angle maximizes the probability of small and large impurities exiting through the comb.

Discussion. The results obtained from this study show that the process of cotton piece sticking to the teeth of the saw drum and separating under the impact of the brush drum in a UXK type cleaning machine depends on the interaction of mechanical, aerodynamic and elastic factors [12]. Although some aspects of these processes have been studied separately in previous scientific sources, this work is scientifically innovative in that it analyzes these stages as a single mechanical model.

As shown in Figure 3, the force of cotton piece sticking to T_1 the saw tooth and $F_1$the resistance reaction of the cotton piece is determined by the balance between During the study, it was found that if the ratio of these forces is not stable, the cotton can slip off the teeth of the saw drum or be unevenly separated. This leads to incomplete separation of small impurities, blockages in the cotton flow and technological losses. This situation is consistent with the results of the saw drum research work of S.E. Hughes and R.W. Baker, but in our experiments the elastic-strength limit of the cotton sliver was estimated in specific quantitative parameters.

It was once again confirmed that the impact of the brush drum is a I_1 decisive factor in the separation of the cotton sliver from the tooth of the saw drum. The optimal impulse interval determined in the research results ensures the complete separation of the cotton from the tooth of the saw drum, while not damaging the fibers. This result significantly clarified the quality recommendations given in previous works and determined the real physical range of the impact force [13]. In particular, the conclusions obtained on the effect of the elasticity and angular location of the brush drum slats on the impulse are an important indicator for practical designers.

One of the important aspects of the research is that the trajectory of the cotton sliver after impact was evaluated both mathematically and experimentally. According to the results, the exit of the cotton at a right angle increases the probability of impurities falling through the comb and ensures a smooth cleaning process. This trajectory model enriched the theoretical approaches previously developed by Uzbek scientists with practical experiments [14].

The influence of the degree of skewness of the combs on the overall system should also be noted. The study clearly showed that reducing the skewness of the comb increases the stability of the cotton flow and improves the degree of separation of large impurities [15]. These results not only confirm the aerodynamic analysis proposed by R.Kh. Rosulov and D.V. Norboyeva, but also shed light on the distribution of forces in the comb-cotton-brush drum triple system.

In general, this study has shown several important conclusions with a scientific basis:

1. The geometry of the sawtooth drum, the impulse of the brush drum and the skewness of the comb should be considered as a single interconnected mechanical system.

2. The optimal parameters of the brush drum operation were determined in a clear mathematical range, which eliminates the uncertainties in previous studies.

3. A scientifically based mechanical model of increasing the cleaning efficiency by modeling the process of separation of cotton lint was developed.

4. The improved version of the UXK machine has been proven to be superior to existing analogues in terms of energy efficiency, fiber safety, and impurity separation efficiency.

Thus, the results of this study offer scientifically sound directions for updating the design of UXK cleaning machines, optimizing brush drum modules, and modernizing primary processing technologies for cotton raw materials. These results are not only theoretically important, but are also expected to have significant practical implications for real production.

Conclusion. The results of this study have shown with reliable scientific evidence that the process of separating a cotton piece from a saw tooth of a drum in a UXK cleaning machine occurs under the coordinated control of mechanical, aerodynamic and elastic factors. The models developed for the saw tooth-cotton-brush drum triple system clearly revealed the theoretical and practical mechanisms of the cotton separation process. The optimal impulse range, drum rotation speed and elastic properties of the brush plates determined during the study determined the mechanical conditions necessary for the safe separation of a cotton piece from the tooth.

In addition, the analysis of the trajectory of the cotton after impact and the stiffness of the combs once again confirmed the high role of these elements in ensuring the stability of the cleaning process. It was found that reducing the comb deformation directly affects the smoothness of the cotton flow and the efficiency of dirt separation. This result fully supported the theoretical views put forward by scientists in the field in practical terms.

In general, the results of the study provide scientifically based, specific recommendations for improving the design of UXK cleaning machines. It has been proven that by comprehensively optimizing the mechanical parameters of the system, it is possible to increase the cleaning efficiency $12-18\,\%$, reduce fiber damage, improve energy efficiency and ensure the technological reliability of the machine.

The scientific value of this work is that for the first time a model has been developed that evaluates the geometry of the sawtooth drum, the impulse of the brush drum, the trajectory of the cotton and the comb as a single mechanical system. This model serves as an important theoretical and practical platform for the modernization of primary processing technologies for cotton raw materials.

The results open up broad opportunities for the creation of a new generation of UXK machines in the future, the introduction of resource-saving technologies and the development of intelligent control systems for the cleaning process. Thus, this research makes a real scientific contribution to the development of the industry and serves to improve cotton cleaning technologies in an innovative direction in accordance with international standards.

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