

ANALYSIS OF THE FIBROUS MATERIAL CLEANING PROCESS AND DEVELOPMENT OF ITS COMPUTER MODEL

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Abstract

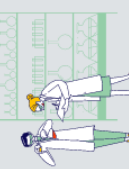
This article is devoted to the analysis of the technological process of cleaning fibrous materials from impurities and the possibilities of its computer modeling. The study examines the difficulties arising from the probabilistic nature of the interaction of fibrous mass particles with the working parts of cleaning machines. An overview of various approaches to modeling technological processes is presented, including geometric, dynamic, probabilistic (Markov), statistical, and simulation statistical models. A detailed analysis of the operation of the spiked drum and grid surface pair of the CL-P preliminary cotton cleaner is carried out. As a result of the impact action of the spikes, the acceleration of the cotton lump increases sharply and then decreases. It was found that along the X-axis, the acceleration initially becomes positive and then negative, which is explained by the transition from decelerated motion before the impact to accelerated motion after the impact. The paper presents differential equations describing the motion of a cotton lump, considering the impact force, air resistance, friction, and centrifugal force. It is shown that these equations cannot be solved analytically and require numerical integration using methods such as Runge-Kutta. The analysis of graphical dependencies shows that the friction coefficient and the rotational speed of the drum significantly affect the velocity of the lump and the path traveled. The obtained results allow for a more accurate description of the cleaning process and optimization of the design parameters of cleaning machines.

Keywords: Cotton cleaner, spiked drum, grid surface, cleaning process, mathematical modeling, computer simulation, impact force, friction coefficient, differential equations, Runge-Kutta method.

Introduction

Worldwide, extensive research is being conducted to improve the efficiency of the cleaning process. The research covers areas such as reducing foreign impurities in the fiber composition, increasing mechanical cleaning efficiency, using computer modeling methods, and applying aerodynamic cleaning technologies.

Significant difficulties arising in the analysis of the cleaning process are mainly related to the fact that the fibrous mass, which interacts with the working parts of the machines, forms a complex system with many elements such as fiber particles, trash and defects, and working organs of various configurations with different laws of motion. Characteristics such as the size,



location, shape, and mass of the particles are random, and the processes of interaction between the particles and the machine's working parts have probabilistic properties. The probabilistic nature of these processes limits the possibilities for analyzing the cleaning process. Typically, we are limited to average indicators, although the process itself depends not only on average values but also on the distribution form of the particle characteristics..

It is possible to model the cleaning process using mathematical analytical methods, but due to the limitations of these methods, it does not allow studying the process in the required detail [1].

An example of this approach is the work of Japanese authors [2-5], who created a model based on practical research—a Markov model—for the change in the mass distribution of particles before and after the machines of a opening-cleaning unit.

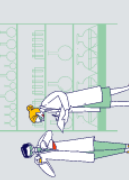
Despite numerous studies on the fibrous mass cleaning process, studying the process itself is difficult. Conducting experiments on opening-cleaning unit machines to study the distribution of particles by mass and the cleaning from trash is very time-consuming.

Similar difficulties in studying systems exist in other fields of science and technology. With the advent of high-performance computers, powerful computer methods are being developed to study such systems. It is known that prospects in this research area have spurred the development of modern computer technologies [6]. The use of computer technologies allows overcoming the limitations of analytical methods and the complexity of practical experiments, and also enables conducting research using computer modeling methods, which are now widely used in all research fields. Therefore, as shown in the scientific works of P. A. Sevostyanov, computer modeling methods are suitable for studying the cleaning process [7-8].

To describe the cleaning process, there are models of different levels:

1. Geometric models, where the kinematics of the movement of fibrous mass particles are considered depending on the speed of the working parts and other factors.
2. Dynamic models, based on material balance ratios for fibrous flows in average values.
3. Probabilistic mathematical models, where the change in the distribution of fibrous mass particle characteristics is considered within the framework of the Markov model.
4. Statistical models based on Monte Carlo methods. These computer models are usually not dynamic. The works of N. P. Buslenko are dedicated to this type of modeling.
5. Simulation statistical models, where both the dynamics of the process and its statistics (which are probabilistic) are implemented simultaneously [6-12]. Obtaining information from simulation statistical models was studied and described in the works of D. Kleijnen [13]. Simulation models of spinning production technological processes were first developed in detail in the dissertation [7] and monographs [8, 14] of P. A. Sevostyanov.

Before constructing a simulation model of a technological process, the incoming flow of fibrous mass is described using the distributions of its various characteristics. Then, random values of the fibrous mass characteristics are generated according to these distributions, which are subsequently transformed according to a specific algorithm that simulates the operation of the system or the course of the process, after which the obtained values are stored. This continues until the statistics of the output distribution are accumulated [15].



To optimize the fibrous mass cleaning process, it is recommended to conduct experiments with computer models of this process, which show how the efficiency of this process changes when design changes are made to the structure of cleaning machines (when filling parameters and the machine's operating mode are changed; when the properties or composition of the fiber are changed).

P. S. Hibare and B. B. Deshmukh [16] analyzed research on the development of an aerodynamic cotton cleaner. According to them, it was noted that the main advantage of the aerodynamic cleaner is that it does not alter the final settings, and also requires compressed air, which is available in spinning mills, and less maintenance.

Cleaning cotton fiber is important due to the presence of fine particles, leaves, and other impurities in its composition; seeds, etc. The cleanliness of the fiber affects the processability of the fiber and yarn [17]. Traditional machines used for cleaning use mechanical opening rollers for opening and cleaning the fibers. Changes in the opening devices at different stages of opening-cleaning units alter the cleanliness of the fibers [18].

The drum-type cotton cleaner developed by Arude, Manojkumar, and Shukla [19] is based on moving cotton along the drum axis. This device consists of main components such as a saw-toothed drum, grid bars, a top cover, and an electric drive. The main technical features of the machine include: cleaner length - 1200 mm, saw drum diameter - 443.4 mm, optimal rotational speed - 225 rpm. Conducted experiments showed that this machine effectively separates large impurities, sand, and dust from cotton. At the same time, the appearance of the produced fibers improves and energy consumption is significantly reduced.

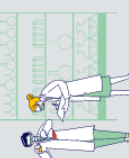
Research conducted by Hardin and Byler [20] identified that one of the main impurities remaining in cotton are plastic and immature fibers. Experiments were conducted on changing the air flow velocity in cotton cleaners to remove these undesirable components. According to the research results, it was found that reducing the rotational speed of the saw cylinder is advisable for effectively separating plastic and immature fibers.

Based on the analysis of the above works, the aim was to improve product quality by improving the design of the preliminary cotton cleaner.

2. EXPERIMENTAL PART

The spiked drum and grid surface of the CL-P preliminary cleaner play an important role in cleaning cotton fiber from impurities. This system is one of the main technological processes of cotton ginning factories and serves as an effective solution in preparing the fiber for the next processing stage.

The spiked drum and grid surface of the CL-P preliminary cleaner play a very important role in cleaning cotton fiber from impurities. This system ensures the efficient operation of cotton ginning factories because the cleaning of cotton fiber from factories affects the success of the entire production process. At the preliminary cleaning stage, various impurities present in the cotton fiber, including soil, plant residues, and other organic matter, are separated. This process improves the quality of the cotton and prepares it for subsequent processing stages.



The spiked drum of the CL-P machine has high efficiency, allowing for the maximum removal of impurities from the fiber surface. The moving spikes of the drum and the grid surface create the air flow and mechanical impact necessary for the correct processing of the cotton. The successful completion of such a process allows preserving the quality of the cotton in subsequent processes and bringing it to the highest level for use in production.

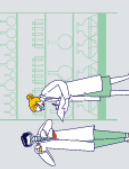
Furthermore, this cleaning system ensures the cleaning of cotton fiber from impurities without mechanical damage, which helps preserve the color and other physico-chemical properties of the cotton. This method of cleaning cotton fiber increases the efficiency of the production process in industrial factories, and also improves the competitiveness of the product in the market.

In the process of effectively cleaning cotton fiber from impurities, the role of the spikes on the spiked drum and the grid surface is considered very important. If the cotton flow passing through each spike is highly contaminated at the initial stage, the cleaning efficiency increases. Because in such a case, when the raw cotton falls onto the spiked drums, it is intensively cleaned, and a dragging process occurs on the grid surface.

In the next stage, as it continues to pass through each spiked drum, the amount of impurities in the cotton decreases. Experiment shows that if there are 8 rows of spikes, with 6 spikes placed in each row and the spacing set at 20 cm, the stability of the cotton flow is ensured, the fibers are not damaged, and clogging situations do not occur. Also, when the spike diameter is 8, 10, 12 mm and the spike length is chosen as 10 cm, the operating efficiency of the drum increases. As optimal design parameters, if the spike diameter is set to 8 mm and the height to 10 cm, the dragging movement of the cotton improves. This serves to further increase the efficiency of the cleaning process.

The cotton cleaning process is carried out in two stages, cleaning first from fine and then from large impurities. Since our research is focused on cleaning cotton from fine impurities, we will mainly dwell on this process. The process of cleaning from fine impurities is carried out in machines having working parts known as the “spiked drum and grid surface pair”. Figure 1 shows the pair of working parts that clean cotton from fine impurities.

During the cleaning process, the cotton is affected by the impact force of the spike F_z , the air resistance force F_a , the friction force of the grid surface F_i , and the gravitational $G=mg$ and centrifugal forces F_m of the cotton. Also, the gravitational force mg and the centrifugal force F_m generate the reaction force N of the surface on the cotton.



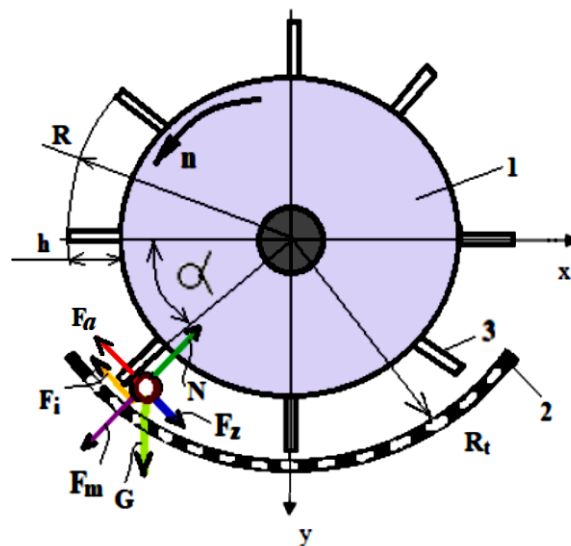


Figure 1. Scheme of the impact of the spiked drum on a cotton lump: 1-spiked drum, 2-grid surface, 3-spike

We find the expression of forces:

The impact force F_z is dependent on the linear velocity of the spiked drum ϑ_b and the coefficient of elasticity c during the interaction of the cotton with the metal surface, and we accept it in the following form:

$$F_z = c\vartheta_b \tag{1}$$

Air resistance force:

$$F_a = k\vartheta_b \tag{2}$$

Centrifugal force F_m :

$$F_m = m \frac{\vartheta^2}{R} = m \frac{(\omega R)^2}{R} = m\omega^2 \cdot R = m \frac{\pi n}{30} R = \frac{\pi}{30} mnR \tag{3}$$

Friction force F_i :

$$F_i = N \cdot f = (F_m + mg \cdot \cos\alpha) \cdot f = \left(m \frac{\vartheta^2}{R} + mg \cdot \cos\alpha \right) f = m \cdot f (\omega^2 R + g \cos\alpha) \tag{4}$$

We formulate the equilibrium equation of the cotton ball with respect to the coordinate axes:

$$m \frac{dv_x}{dt} = -F_m \cdot \sin\alpha - F_u \cdot \cos\alpha + F_z \cdot \cos\alpha - F_a \cdot \cos\alpha \tag{5}$$

$$m \frac{dv_y}{dt} = mg + F_m \cdot \cos\alpha - F_u \cdot \sin\alpha + F_z \cdot \sin\alpha - F_a \cdot \sin\alpha$$

(1), (2) (3) va (4) taking into account the equations, we change the form of equation (5):

$$m \frac{dv_x}{dt} = -\omega^2 m R \cdot \sin\alpha - [mf(\omega^2 R + g \cdot \cos\alpha) + (c - k)\vartheta] \cdot \cos\alpha \tag{6}$$

$$m \frac{dv_y}{dt} = mg + \omega^2 m R \cdot \cos\alpha - [mf(\omega^2 R + g \cdot \cos\alpha) + (c - k)\vartheta] \cdot \sin\alpha$$

From this we obtain the following::

$$\begin{aligned} \frac{dv_x}{dt} &= -\omega^2 R \cdot \sin\alpha - \left[f(\omega^2 R + g \cos\alpha) + \frac{c-k}{m} \vartheta \right] \cdot \cos\alpha \\ \frac{dv_y}{dt} &= g + \omega^2 R \cdot \cos\alpha - \left[f(\omega^2 R + g \cos\alpha) + \frac{c-k}{m} \vartheta \right] \cdot \sin\alpha \end{aligned} \tag{7}$$

α taking into account its change depending on the angular velocity of the spiked drum, we accept the following:

$$\alpha = \omega t \quad (8)$$

Substituting, the following equation is derived:

$$\begin{aligned} \frac{dv_x}{dt} &= -\omega^2 R \cdot \sin \omega t - [f(\omega^2 R + g \cos \omega t) + \frac{c-k}{m} \vartheta] \cdot \cos \omega t \\ \frac{dv_y}{dt} &= g + \omega^2 R \cdot \cos \omega t - [f(\omega^2 R + g \cos \omega t) + \frac{c-k}{m} \vartheta] \cdot \sin \omega t \end{aligned} \quad (9)$$

Where: $\alpha = \omega t$; $\omega = \frac{\pi n}{30}$, rad/s; $g = 9.81 \text{ m/s}^2$

These equations cannot be integrated analytically. We will perform the integration numerically, specifically using the Runge-Kutta method, on a computer.

We accept the initial conditions:

$t_0=0$; $\alpha_0=30^\circ = 0.17 \text{ rad}$; $n=350;500;600 \text{ rpm}$;
 $R=200 \text{ mm} = 0,2\text{m}$; $m = 0,001; 0,0015; 0,01\text{kg}$;
 $c = 0.1 \text{ kg/c}$; $k = 0,1 \text{ kg/c}$; $f = 0.2; 0,4; 0.8; 1.2$)

3. RESULTS AND DISCUSSION

If we accept that the cleaning process ends at time $t = t_0$, after this time $\alpha = 150^\circ$ and the cotton leaves the grid surface. In this case, the calculation ends at $\alpha = 150^\circ = 0.83 \text{ rad}$. The analysis of the equations obtained based on the given conditions and parameters is presented in Figures 2-5.

Figure 2 shows the graph of the acceleration change of the cotton lump under the influence of impact. At the beginning of the cleaning process, the seed has not yet fallen onto the grid surface. Therefore, at the initial time ($t = 0$), the velocity of the cotton ($v = 0$) and the forces acting on it approach zero.

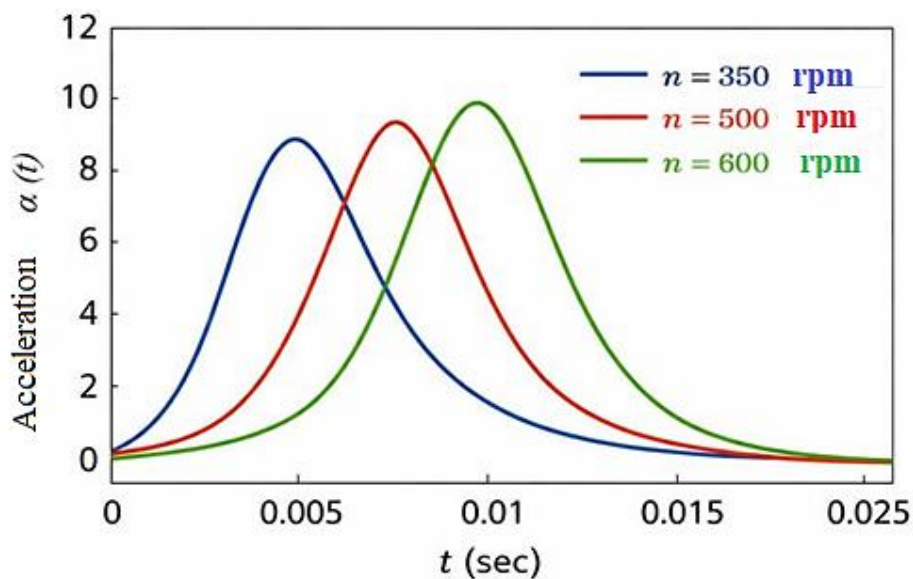


Figure 2. Change in the acceleration of the cotton lump under the influence of impact

Graph analysis shows that at ($t > 0$), $a(t)$ increases with a sinusoidal oscillation. These considerations connect the physical situation with graphical analysis and explain the sinusoidal oscillation through the initial conditions.

At the beginning of the cleaning process, i.e., when the seed has not yet fallen onto the grid surface, it allows us to assess the initial state of the fiber as static. Therefore, at the initial time ($t = 0$), the velocity of the fiber ($v = 0$) is equal to zero. In this state, the forces acting on it, i.e., the gravitational force, the reaction force, and the inertia forces arising from vibration, approach zero.

Graph analysis shows that over time ($t > 0$), the fiber falls onto the grid surface and begins to move under the influence of an oscillating environment. The velocity of the fiber increases according to a sinusoidal oscillation pattern.

This model represents the motion of the fiber in situations where it interacts with an oscillating surface. The sinusoidal oscillation imparts momentum to the fiber's motion, bringing it into the dynamic state necessary for the cleaning process.

Figure 3 presents the analysis of the changes in relative and absolute velocities over time for friction coefficient values ($f = 0.2; 0.8$). According to these, at a low friction coefficient value, the velocities increase sharply, while at a high friction coefficient, the velocities increase with lower intensity.

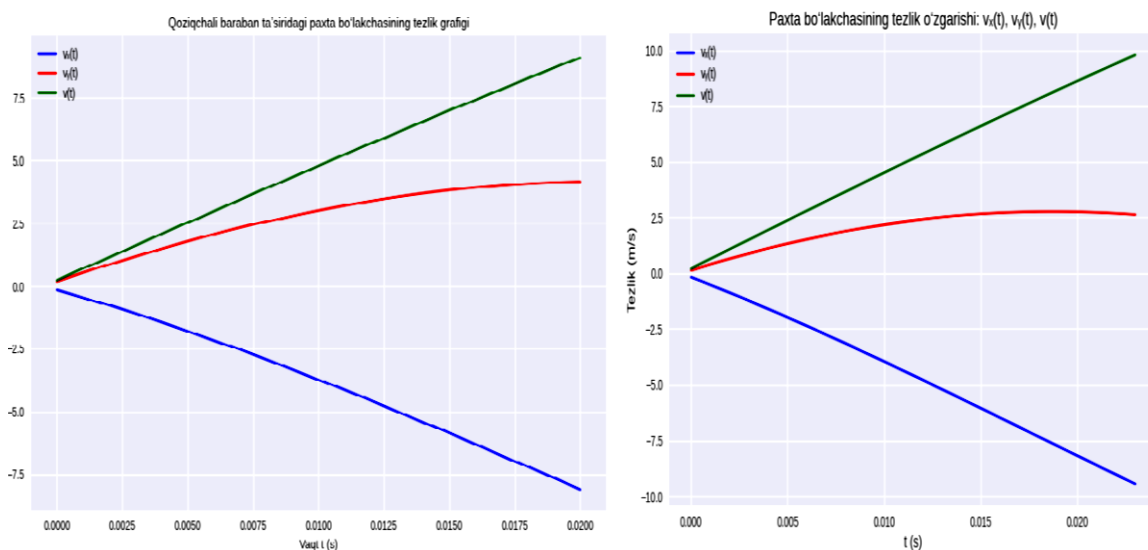


Figure 3. Changes in relative and absolute velocities over time

Figure 4 presents the analysis of the change in the path traveled by the cotton fiber over time for drum rotational speed values ($n = 350; 500; 600$ rpm). According to these, at a low drum rotational speed value, the displacement is slow, while at high rotational speeds, the path increases with higher intensity.

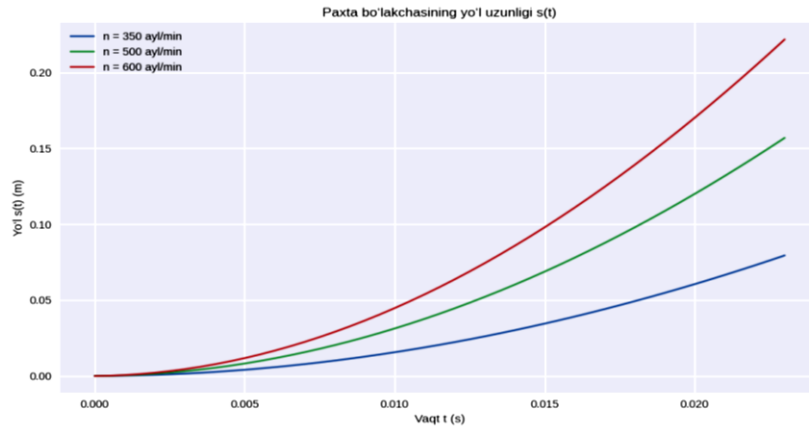


Figure 4. Changes in the path traveled by the cotton fiber over time

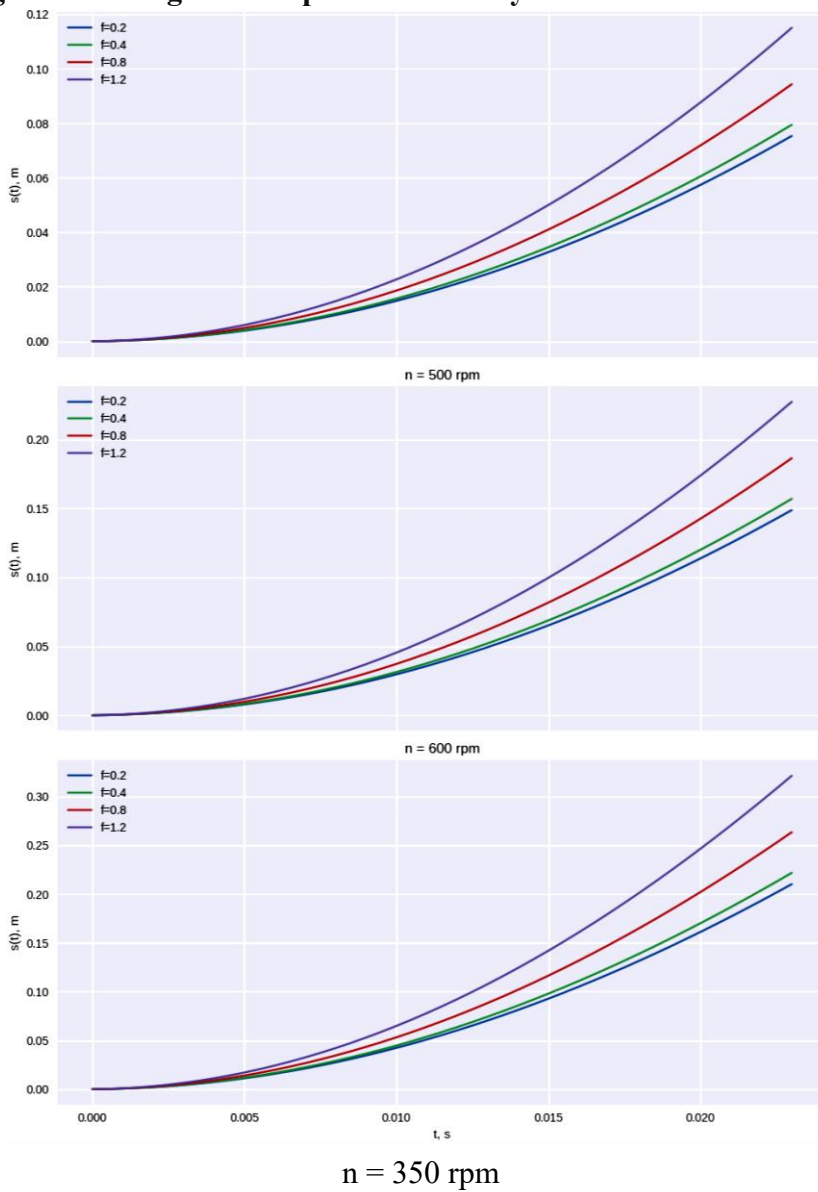


Figure 5. Changes in the path traveled by the cotton fiber over time at different friction coefficients and rotational speeds

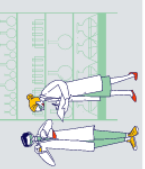


Figure 5 shows the change in the path traveled by the cotton fiber over time at different friction coefficients and different speeds of the working drum.

If we pay attention to the graphs (see Figures 2-5), we can observe the change in the acceleration of the cotton lump along the X and Y axes over time in the cleaning zone. Indeed, as a result of the impact action of the spikes, the acceleration of the cotton lump increases sharply and decreases as the impact subsides. The magnitude of the impact force acting on the cotton lump can be determined by the maximum value of the acceleration.

It can be observed that along the X-axis, the acceleration initially reaches a positive value and then becomes negative. The reason for this is that before the impact, the cotton moves by its own inertia and has a negative value, i.e., it is in decelerated motion. When impacted by the grid, its velocity increases sharply, and since it then undergoes accelerated motion, its acceleration becomes positive.

Along the Y-axis, however, the acceleration does not change to negative; instead, this acceleration tends to decrease slowly over a short period of time.

4. CONCLUSION

The ability to ensure consistently efficient cleaning of raw cotton from the beginning to the end of the cleaning system significantly increases the efficiency of the production process. Here, at each stage, the cleaning of cotton fiber from impurities is brought to a maximum level without losing its quality. The efficient operation of the system ensures that every part of the cotton fiber is cleaned to the same degree, which prevents impurities from remaining in any part. As a result, at the end of the cleaning process, the fiber is of high quality and in a clean state.

Such an approach helps not only to increase cleaning efficiency but also to ensure the stability of the technological process. Systems that ensure stable operation serve to preserve the quality of the cotton fiber, while also reducing production interruptions and increasing the overall efficiency of the process. High cleaning efficiency facilitates the preparation of cotton fiber for subsequent processing stages, thereby creating the opportunity to make the entire production process faster and more efficient.

Furthermore, a high level of cleaning efficiency is important for the marketability of cotton. When clean, high-quality cotton is brought to market, its sale becomes easier, which is economically beneficial for producers. The implementation of such systems serves to increase the competitiveness of the cotton industry and achieve success in the world market.

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