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A STUDY OF THE INFLUENCE PRODUCED BY THE DYNAMICS OF THE WORKING BODIES OF COTTON-PROCESSING MACHINES ON THE COTTON FIBRE QUALITY

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Cotton mass is considered as a compressible porous two-component medium, consisting of a mixture of cotton fibres and air included in the porous medium, which is essential in dynamic treatment processes and requires consideration when planning technological modes.

It was found that the speed of sound in multicomponent media significantly decreases with an increase in the content of the gaseous component. With a certain content of components, it can become less than in each of the components separately. This is due to the fact that with an increase in the content of the gaseous component, the density of the medium increases insignificantly, and the compressibility of air sharply decreases in the pores.

As a result of the research, it was found that the value of the dynamic change in the density of cotton raw materials can significantly exceed its density during static compression. This kind of influence can have both adverse and desirable effects on the primary stage of cotton processing.

The dynamic characteristics of raw cotton as an object of mechanical technology were studied. The values of the speed of sound as a function of the density of cotton raw materials were determined on the basis of the theory of a two-component porous medium. The types of the dynamic compression curve of raw cotton have been established. Experimental studies on the compressibility of raw cotton are generalized.

From the analysis of the cleaning processing of fibres and seeds on cleaning machines, it follows that when assigning a technological processing mode, it is necessary to comply it with the value of the sound speed for a given density of raw materials. It is necessary to avoid such rates of penetration of the working bodies into raw materials that are commensurate with the speed of sound at a given raw material density. This local dramatic increase in cotton media characteristics is a significant cause of fibre damage

Keywords: fibrous material, multicomponent medium, speed of sound, dynamic processes, layer deformation

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1. Introduction

One of the fundamental characteristics of a fibrous material that determines its dynamic behaviour is the speed of sound propagation in it. The magnitude of the speed of sound determines the boundary at which the phenomenon of compressibility of the processed cotton medium begins to manifest itself while the smoothness, pressure and temperature in it significantly increase. This effect can adversely influence the damage to cotton fibres but in some cases can be positive.

Research on the speed of sound can result in its direct practical application in matters of cleaning technology by vibration and wave methods. The need to develop and implement such methods is due to the following.

The existing mechanical and technological processes for the primary processing of raw cotton – cleaning from fine impurities, ginning (saw and roller), fibre cleaning, in-plant and shop transport – produce a dynamic effect on the processed product. This is due to the difference in size, windage and other properties of cotton and fibre, cotton and impurities, which take place in a given process.

In such cases, the impact on cotton is close to shock; those are most often weakly nonlinear dynamic processes at technological speeds of 5–12 m/s and transport speeds up to 25–30 m/s. The time of impact interaction of raw cotton and fibre with grates and pegs is 0.0020–0.0040 s, depending on the degree of irradiation of raw cotton, fibre moisture, and other process parameters.

In practice there are no longer any reserves for the development of these technologies, which have been well studied for a long time. On the way to increasing the efficiency of the processes, there is a barrier that limits product quality. Although the capabilities of the processes can sometimes be partially expanded through special measures, there have been no significant shifts so far.

Cotton is a compressible viscous medium. It should be noted that the issue of the displacement of such a medium is currently very little studied. Practical problems for this kind of media are solved by combining the results obtained separately for an ideal compressible fluid and for a viscous incompressible fluid.

In addition to the static compaction of raw materials, which is usually carried out when pressing in a closed volume of space, there is also the effect of dynamic compression when the working body is introduced into the raw material at a certain speed. This effect is most significant when the speed of the working body is comparable to the speed of sound in the medium being processed. This significantly increases the density, pressure, and temperature of the raw material on the surface of the working body. This dynamic effect of compression of the medium adversely affects the damageability of cotton fibres.

Therefore, a study of damage arising in cotton mass under dynamic impact during technological processing processes is relevant.

2. Literature review and problem statement

In [1], the difference from the models of solids known in mechanics, which at small deformations obey linear laws, was considered; the mass of raw cotton only at very high densities can approach viscoelastic media in its deformation law.

Such directions as modelling the laws of deformation and change of shape, volume of raw cotton under the influence of static and dynamic loads have not been investigated. It is still necessary to study the problems of questions that help to find an answer as to what are the properties of cotton in dynamics and what processes can be implemented in this case.

Study [2] presents the result of research on the cleaning processing by cleaning machines where fibres and raw cotton seeds are subjected to repeated dynamic effects. In practice, after the completion of cleaning, the fibres are significantly damaged, subject to deformation of the plasticity limit and have lost their physicomechanical and biological properties, which are valuable for obtaining high-quality products. The experiments by the researcher were not performed correctly in terms of the choice of the frequency of the natural oscillations in the system, and, at least, the values of the impact force obtained in this work were an order of magnitude higher than the actual ones.

In works [3, 4], the issue of optimization of fibre pressing into bales was investigated. In this case, for the mathematical description of such a process, formulas were derived expressing the relationship between the pressure and the volume of the fibre mass. It was shown there that when cotton is pressed, the pressure on the chamber walls is significantly high; therefore, significant frictional forces appear between the fibre and the chamber walls. Research has not been completed in such areas as modelling the laws of deformation and change in the shape and volume of raw cotton under the influence of static and dynamic loads.

In work [5], the fundamentals of the mechanics of the process of interaction of raw cotton fluffs with the working bodies of the coarse impurities cleaner section were given. The author researched the processes of fixing and removing raw cotton from the saw set as well as the impulses of the impact interaction of the fly with the grate. The dynamics of the process was used by the author in the calculation of the values of the shock impulse. At the same time, a transition to the magnitude of the impact force is necessary, which requires knowledge of the characteristics of the dynamic rigidity of the material and the compilation of a model that is inherently adequate to the studied process scheme.

It is noteworthy that in works [6, 7] devoted to the issues of wave dynamics in porous multicomponent media such as soil, sand, gravel, etc., it was stated that the theoretical calculation for the magnitude of the speed of sound would give a result that is somewhat underestimated in comparison with reality.

In [8], the issue of compression of small samples (about 20 g) of textile fibres in the mass was considered at large intervals of variation of the external load and at its low application rate. However, for full-scale technological operations in real presses, it is difficult to apply the data obtained on small samples. These data are not linked to the solution of the problems of packing large masses of textile fibres.

In [9], studies were carried out on the introduction of a rotary-type working body of an installation that simulates the development of a cotton pack. The studies were devoted to the analysis of damage to raw materials when digging tunnels in the packs of raw cotton and the choice of optimal parameters of working bodies. However, in [9] there was insufficient data on the forces and stresses that arise inside the fibres during dynamic compression of the mass of raw materials, which cause deterioration or destruction of fibres.

In study [10], a mathematical description of the process of pressing cotton fibres into bales was given and the characteristics of such a process were established. The study of the sought dependences was based on the mathematical description of the Kelvin-Voigt mechanical model applied to textile fibres. The work did not investigate such issues as the appearance of defects in cotton raw materials after passing through the cleaners and other technological machines, the compaction of individual particles along the periphery, the deterioration of the fibre, and felting with the formation of soft defects.

The practice of processing fine-stapled raw cotton has shown [11, 12] that cleaning raw cotton on cleaning machines is accompanied by significant damage to the seeds, which increases the amount of defects in the fibre due to the skin with fibre and broken seeds. Therefore, in order to improve the quality of fibre and seeds in many ginneries, the influence of the dynamics of the working bodies of cotton processing machines was reduced due to the rotation frequency of the working bodies. The works did not include the consideration that in the technological mode of processing it is necessary to take into account the magnitude of the sound speed for a given density of the raw material and to avoid such rates of penetration into the raw material of the working bodies that are commensurate with the speed of sound.

A significant contribution to the creation of the scientific foundations of the technology for cleaning raw cotton was given in works [13, 14]. In these studies, the dynamics of the process was researched as to the main elements of the interaction of working bodies with raw cotton. It was shown that the process and its efficiency are determined by two counter factors – the quality of raw cotton and the efficiency of removing impurities. However, in [13, 14] there is insufficient data on the forces and stresses that arise inside the fibres during dynamic compression of the mass of raw materials, which cause deterioration in the quality or destruction of the fibres.

Research has not been completed in such fundamental areas as modelling the laws of deformation and change in the shape and volume of raw cotton under the influence of static and dynamic loads.

To date, the question of the magnitude of the speed of sound in the cotton medium, during the introduction of the working body into it, remains unexplored. This does not allow to reasonably establish the value of the rate of introducing the working bodies of the machines into the raw material.

3. The aim and objectives of the study

The aim of the work is to determine the influence of the dynamics of the working bodies of cotton processing machines on the quality of raw cotton.

To achieve the goal, the following tasks were set and done:

– to determine the speed of sound propagation in a cotton medium,

– to research the dynamics of the loading process of raw cotton as a model of a two-component medium,

– to study the dynamic effects on the quality of the fibre at small transonic deformations of the cotton medium,

– to examine the stresses in the cotton medium when the working bodies of machines are introduced into it.

4. Determination of the speed of sound propagation in a cotton medium

In works [7, 8], experimental research was carried out in the field of cleaning technology by vibration and wave methods. It revealed the phenomenon of non-perception by raw cotton of ultrasonic frequencies (30 kHz and more), which did not penetrate deep into the fibrous medium. Lower frequencies (up to 20 kHz) made it possible to achieve a cleaning effect of 50–76 % at amplitudes of 1–4 mm. However, for such cleaning, the cotton had to undergo 1,000–2,500 vibrations or vibration impacts for 1–2 minutes.

If in air the speed of sound is 330 m/s, then in a linearly oriented fibre it is already 1,500–1,700 m/s; cotton yarn will have the speed of sound 700–750 m/s, and in wool it is 100–120 m/s. In the bulk of the fibre, this speed varies from several tens to hundreds of meters per second as a function of density, humidity, and grade – the main characteristics of its state.

Below, theoretically and experimentally, the question of the speed of propagation of sound as well as ultrasonic waves in the bulk of raw cotton is investigated.

In [9], it was shown that the amount of dynamic change in the density of cotton raw material can significantly exceed its density under static compression. This kind of effect can have both adverse and desirable effects on the primary cotton processing.

When developing a model for the mechanical description of the dynamics of the process of introducing the working body of the machine into cotton raw materials, the following was assumed. There is such a platform on the surface of the working body on which the particles of raw material run perpendicular to it and are completely inhibited. The particle velocity becomes zero. On such a site, it can be approximately assumed that the pressure distribution here is close to constant, and at the edges of the site, the pressure drops.

Raw cotton is a compressible medium with intense internal friction of the layers during their mutual displacement. Since the pressure in the central part of the mentioned area is close to constant, the layers of cotton in this place are compressed evenly over the layers, without mutual displacement. Therefore, the effect of internal friction in the central part of the site can be ignored and not taken into account in the equations of motion.

Based on the foregoing, to calculate the dynamic phenomena of compaction of raw materials at the sites of maximum compression, it is possible to use the one-dimensional theory of motion of a compressible ideal liquid (gas). For the steady motion of the medium, the system of three equations relating the pressure p, density ρ, and velocity v of particles in the medium has the form of:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=-\frac{1}{\rho}\frac{\partial p}{\partial x}, \tag{1}$$

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho v)=0, \tag{2}$$

$$p=f(\rho), \tag{3}$$

where

$$\frac{\partial p}{\partial t}=0,\quad \frac{\partial v}{\partial t}=0.$$

Here (1) is the equation of one-dimensional motion, (2) is the equation of continuity of the medium, and (3) is the equation of the state linking the pressure p and density ρ of the medium; v is the velocity of the raw material particle. The system of equations (1)–(3) makes it possible to draw conclusions about the nature of the behaviour of the pressure p and density ρ for cotton mass when the working bodies of processing machines are introduced into it.

Equation (3) $p=f(\rho)$ is the so-called equation of the state that relates the pressure p and the density p of the medium. Depending on the nature of the medium, its physical and mechanical properties, and the rate of external loading, the equation is found experimentally.

The equation of the state $p=f(\rho)$ for static loads is well known in the technological processes of pressing cotton when the loading rate of the volume of the medium is very low and the air component of the medium can freely leave the pressed volume.

During pressing, the force load is perceived only by cotton fibres (Fig. 1). The air component of the raw material is filtered at a low speed without resisting the external power load.

In this case, only cotton fibres are virtually absent in the compression process. In [3], it was noted that studies under uniaxial compression obtained a pressing curve from pressure on the fibre:

$$p = k\rho^{\gamma}, \tag{4}$$

where k is a constant characterizing the state of the cotton fibre being pressed, and the compression adiabatic index for medium and high fibre densities is $\gamma=3$.

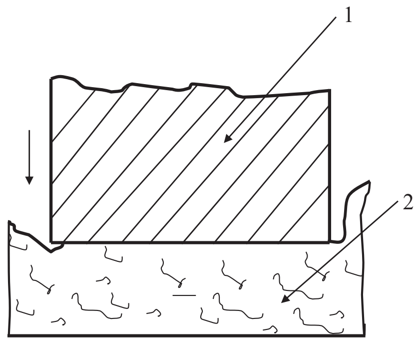

Fig. 1. A scheme of movement of a cotton particle under the influence of a stamp of a cotton press: 1 is the metal stamp; 2 is the raw cotton

This compression curve is actually the adiabat of static compression of the fibrous material.

It can be noted that the adiabatic value of compression for air is $\gamma=1.4$; for heavy gases formed during the detonation of explosives, it is $\gamma=3$. In their expression, (4) and the compression adiabat for a heavy gas are indistinguishable. On this basis, a medium consisting of cotton fibres can be likened to some kind of gas, and in the future it is possible to approach the analysis of the issue from the point of view of gas dynamics.

The scheme of the technological process of compaction is such that initially cotton fibre in the form of a loose mass with a bulk density of 12–15 kg/m^3 is compacted to a density of 150–200 kg/m^3 and then is pressed to a density of 550–600 kg/m^3.

In connection with the indicated scheme of operations for compacting cotton fibres, in [6] the following regularities for the compression adiabat are given.

The dependence of compaction density on fibre pressure is:

$$\rho = 83.3\sqrt[3]{p}. \tag{5}$$

at a specific pressure of $120<p<2{,}000$ N/cm^2, but if the specific pressure is $10<p<120$ N/cm^2, then the formula takes the form of:

$$\rho = \left(288 - 0.64\sqrt{p}\right)0.47\sqrt[3]{p} - 55.$$

Finally, with $p<10$ N/cm^2, the dependence is as follows:

$$\rho=25+18.5p. \tag{6}$$

Here the relationship between density and pressure is linear. This can be explained by the fact that at low density the volume fraction of cotton fibres in the total mixture of fibres and air is also small. With a low density of the mixture, the main resistance under dynamic action can be produced by the air included in the composition of raw cotton. However, during static compression of the mixture, almost all air is filtered from the raw material and its force effect is not felt.

$$p = 10^4 \frac{1}{83.8^3}\rho^3. \tag{7}$$

Taking into account the fact that $84.8^3 \approx 600{,}000$, finally:

$$p = \frac{1}{60}\rho^3. \tag{8}$$

The speed of sound is determined by equation (6). It follows from (8) that:

$$s = \frac{dp}{d\rho} = \frac{1}{20}\rho^2, \tag{9}$$

and in the final form:

$$s=0.21\rho. \tag{10}$$

In (10), the range of the density change will be $420<\rho<1{,}060$ kg/m^3; these values for density can be obtained from (5), for which the pressure is $120<p<2{,}000$ N/cm^2.

From the obtained formula (10) it follows that with the medium density of $\rho=420$ kg/m^3 the speed of sound will be $s=90$ m/s, and with $\rho=1{,}060$ kg/m^3, it will be $s=226$ m/s.

In the course of these calculations, it was assumed that cotton fibres, enclosed in the volume of the medium, represent some kind of gas with the equation of state:

$$p = \frac{1}{60}\rho^3.$$

For small deformations of the volume of cotton fibres, the dependence is:

$$s^2 = \frac{dp}{d\rho}.$$

In this case, the influence of the air component included in the composition of raw cotton on small dynamic disturbances of the medium during the passage of a sound wave was ignored.

Under these assumptions, the obtained values of the velocities $s=90$ m/s and $s=226$ m/s at the corresponding densities $\rho=420$ kg/m^3 and $\rho=1{,}060$ kg/m^3 do not reflect well the real picture of the relationship between the speed of sound and the density of the medium. This is due to the fact that although at high mixture densities the volumetric content of the air component in the medium is small, even in small dynamic disturbances of the medium, both cotton fibres and air in the pores between the fibres bear a force load. The dynamic effect of air included in the cotton medium is significant even with small dynamic disturbances during the passage of a sound wave.

Let us now consider the region of low densities and pressures $0<p<10$ N/cm^2. Here the following formula is valid [13]:

$$\rho=25+18p. \tag{11}$$

From (9), the pressure p can be expressed as a function of the density ρ:

$$p=\frac{\rho-25}{18.5}\ \text{N/m}^2.$$

For 1 m^2, the pressure will accordingly be:

$$p=10^4\frac{\rho-25}{18.5}\ \text{N/m}^2,$$

or

$$p=540(\rho-25). \qquad (12)$$

From (12) it follows that:

$$s^2=\frac{\partial p}{\partial\rho}=540,$$

and hence the speed of sound is s=23 m/s.

The result has turned out to be independent of the density ρ in the range of densities $25<\rho<210$ kg /m^3. This value for the density was obtained from (11) for the pressure boundaries of $0<p<10$ N/cm^2.

It can be argued that the obtained result with s=23 m/s is strongly underestimated in comparison with the actual one and significantly differs from the fact. The question of the speed of sound in the region of low densities and pressures requires more detailed experimental studies. From physical considerations, it is clear that the magnitude of the speed of sound with a decrease in the volumetric content of fibres in the mixture and an increase in the volumetric content of air should increase and tend to the limit of s=330 m/s of the speed of sound in air. This will be an extreme condition for the mixture when there are no fibres and only air remains.

5. Research on the dynamics of the process of loading raw cotton as a model of a two-component medium

A cotton medium is a substantially porous medium consisting of a composite mixture of randomly oriented raw material fibres and air filling spaces between the fibres. Air is present in such a medium in the form of small volumes separated from one another by cotton fibres. The air component of such a medium can be involved in processing operations in an interconnected process of changing pressure and density. The air trapped inside the raw material does not have time to completely flow out by the time of introducing the working body into the medium. This has an impact on the dynamics of the technological processes.

In this regard, the processed medium must already be considered as two-component – air and the actual cotton fibres. Therefore, it is of undoubted interest to study the dynamics of the loading process for such a model of a two-component medium.

There are a large number of porous materials of natural origin that include air and gases. These are soil, sand, forest, peat, gravel, as well as water and oil with air and gas bubbles. The dynamic properties of all the listed materials significantly depend on the content of air trapped in them.

Models of multicomponent media [7], which have received wide experimental confirmation, are well applicable to substances of this kind.

Based on the foregoing, the theory of multicomponent media will be used to study questions about the magnitude of the speed of sound in cotton raw materials in a wide range of changes in their density.

It is assumed that under the action of external loads on a continuous medium such as cotton, each of its two components is compressed according to its own law, determined during the compression of each individual medium.

It is known that when denser cotton fibres are compressed, less dense air bubbles between them are compressed, too. However, when the compression wave passes from a denser medium, the speed of sound decreases significantly and the weakened wave is not able to strongly compress the elementary volume of air.

On the basis of this, the compression of air in bubbles under dynamic loads is assumed to occur, as under static loads, according to the Poisson adiabat, and not according to the Hugoniot shock adiabat [7].

The speed of sound in a medium is one of its most important characteristics, since it determines the speed of propagation of weak disturbances.

The expression for the speed of sound s in a two-component medium looks like this:

$$s^2=\frac{1}{\rho_0}\left(\frac{\alpha_1}{\rho_1 c^2}+\frac{\alpha_2}{\rho_2 c^2}\right)^{-1}, \qquad (13)$$

where α_1 and α_2 are the volume contents of the gaseous and cotton components; s_1 and s_2 are the speeds of sound in the air and the cotton fibres at normal atmospheric pressure.

The density of the medium is:

$$\rho_0=\alpha_1\rho_1+\alpha_2\rho_2,$$

where ρ_1 and ρ_2 are the density of the air and the cotton fibres, with $\alpha_1+\alpha_2=1$.

For air, it is assumed that the weight density (volumetric weight) is ρ_1=1.2 kg/m^2 and the speed of sound is s_1=330 m/s; for cotton fibres, the weight density is ρ_2=1,200 kg/m^3 and s_2=1,700 m/s, respectively.

The values of the speeds of sound, calculated in accordance with (13), for a wide range of raw material densities are given in Table 1.

Table 1

The results of calculating the speed of sound s versus the density ρ of the raw material

Density ρ, kg/m^3	1.2	5.0	25.0	100	200	300	400	600
Speed s, m/s	330	160	73	38	28	24	22	21

The analysis (Table 1) for the speed of sound in the cotton mass shows that, starting from s=330 m/s, for air without fibre impurities, this speed further sharply drops in its value even with an insignificant amount of cotton fibre in the mixture.

Thus, the speed of sound of the disassembled two-component cotton medium has a significantly lower effect than in each of the two components (air with s=330 m/s and cotton fibre with s=1,700 m/s) separately.

6. Research of the dynamic effects on fibre quality at small transonic deformations of the cotton medium

It is assumed that for this model of a two-component cotton medium, the air in the pores of the system does not have time to escape during the dynamic action. Such conditions are created when, for example, the exposure time of the working body and its density are large enough. This creates damping for the flow and filtration of air with a sufficiently large coefficient of resistance.

It is known from the theory of acoustics that the speed of sound s is related to the pressure p, the density of the medium ρ, and the dynamic adiabat of compression as follows:

$$s^2 = \frac{dp}{d\rho}, \tag{14}$$

i. e.,

$$dp = s^2 d\rho. \tag{15}$$

The region of continuous change in the pressure p and density ρ in (15) can be further divided into sufficiently small discrete sections Δp and $\Delta\rho$ and instead of (15) its approximate value can be written as:

$$\Delta p_i = s^2 \Delta\rho_i. \tag{16}$$

The last formula in the form of (16) makes it possible to numerically calculate a fluctuation of the pressure Δp for the small sections of $\Delta\rho$. The value of s for each section is considered fixed and is taken from Table 1, respectively, for each section of densities $\Delta\rho$.

Summing then all elementary values of (16) in the form of:

$$p = \sum \Delta p_i = \sum s^2 \Delta\rho_i, \tag{17}$$

it is possible to obtain a sufficiently approximate value of the pressure p for the adiabat of the dynamic effect on the cotton medium for any arbitrary density $\rho = \sum \Delta\rho_i$.

It should be noted that in (17) the value is of the mass density magnitude of $(\text{kg}\cdot\text{s}^2)/\text{m}^4$; therefore, instead of the previously used weight density of $\Delta\rho$ kg/m^3, here it is necessary to introduce into (17) the expression:

$$\frac{\Delta\rho}{g}\frac{\text{kg/m}^3}{\text{m/s}^2} = \frac{\Delta\rho\cdot\text{kgs}^2}{g\cdot\text{m}^4}.$$

Then the dimensions of both parts in (17) will look the same as kg/m^2.

After the values of the speeds of sound s in a two-component medium are determined according to Table 2, it is possible to calculate by (16) and (17) the value of the pressure p throughout all changes in the density ρ of the raw material.

The selected results of such calculations are shown in Table 2.

Table 2

The results of calculating the values of the pressure p on the density ρ of the raw materials

Density ρ, kg/m^3	1.32	2.0	5.0	10	25	50	100	150	200	300	350
Pressure p, N/cm^2	1.19	6.5	18.1	28.3	40.2	49	58.5	64.2	68.5	75	77.5

Since Table 2 reveals the dependence of pressure as a function of the density of the raw materials $p=f(\rho)$, this dependence can be plotted graphically (Fig. 2) in the form of Curve 2. This curve will represent the desired relationship between the pressure p and the density ρ in a two-component cotton medium with small dynamic disturbances. This dependence has a form typical for an elastic-plastic medium (Fig. 2). It is believed that the air trapped inside the cotton blend does not leave its pore space. In this case, dynamic compression is determined by the common elastic properties of cotton fibres and air trapped inside the cotton medium in the pores.

Curve 1 in Fig. 2 (obtained from the results of the experimental tests) is the curve of the static compression of cotton fibres. With a sufficiently slow compression of the cotton mass, it can be said that the entire mass of air has time to leave the volume of the continuous medium. The compression process is determined only by the elastic properties of the cotton fibres.

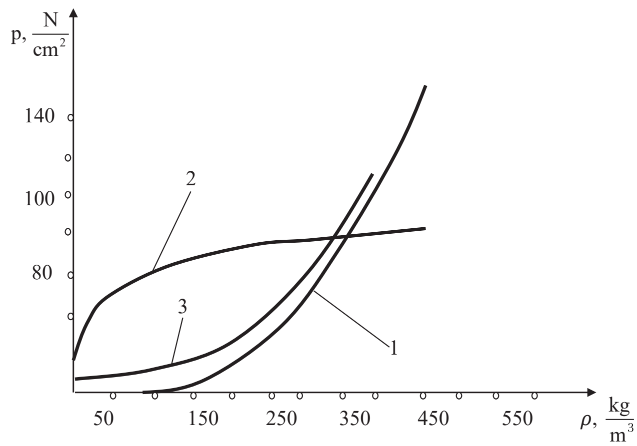

Fig. 2. The type of dependence of the pressure p on the density ρ of cotton raw materials under static and dynamic loads

Apparently, in real processes of compressing cotton mass, part of the gas trapped between the fibres of cotton raw material has time to leave the volume of the two-component medium. In this case, the real curves reflecting the dynamics of the compression process are located in the section of the p, ρ plane between Curves 1 and 2.

It should be noted that there is a similarity between Curve 2 in Fig. 2 of the dynamic state of cotton raw materials and curves describing the state of matters such as non-water-saturated soils. At low pressures, Curve 2 will be concave, and at high pressures, it will be convex to the ρ axis. For unsaturated soils of this kind, the curves were obtained as a result of numerous experiments.

To confirm the reliability of all previously obtained theoretical results and conclusions, one can refer to the results of experimental works [11, 12] determining the efforts applied in the process of cleaning cotton. The experiments were carried out with the introduction of splits into raw cotton at different depths and different densities of the raw material (Fig. 2, 3).

In Fig. 2, Curve 3 depicts the course of real dynamic forces depending on the density of $\rho = 125;200;250$ kg/m^3 in a cotton bundle. In this case, the rotating peg is introduced to a depth of $l = 110$ mm at the peripheral speed of $V = 3.5$ m/s with a feed at $S = 20$ mm/rev and the moisture content of cotton $W = 7.8\%$. The effective splitting area can be taken equal to F=1.5–2 cm^2. In this section of the splitter tip, it can be assumed that the cotton mass is fully compressed and inhibited without flowing around the rest of the splitter shaft. Let us dwell on the value of F=1.5 cm^2.

Fig. 3 shows that as the depth l of the peg decreases, the p N/cm^2 stress also decreases for all densities ρ (under the same experimental conditions as for Curve 3; V=3.5 m/s, S=20 mm/rev) considered in the experiment. This means that Curve 3 in Fig. 2 will tend to the static compression Curve 1 as the splitting depth l decreases.

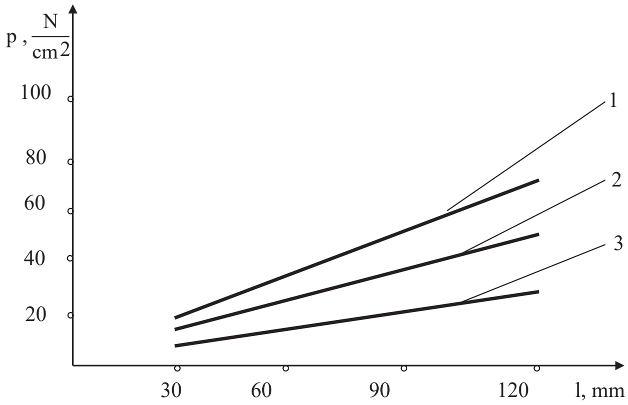

Fig. 3. The dependence of the pressures p on the depth of the splitter l

This can be explained by the fact that as the penetration depth l decreases from 110 mm to 30 mm, the possibility of air filtration and escape from the pore space in the cotton bundle increases. Then the dynamic load Curve 3 tends to the static compression Curve 1, in the construction of which the influence of the remaining air does not affect the course of the compression process.

It should be noted that the output for the speed of sound propagation in a mixture of perturbations of infinitely small amplitudes was previously proposed in [9]. The result obtained in that work actually coincides with expression (13). Subsequently, the result of [9], with more extensive justification, was confirmed for a perturbation of arbitrary amplitude.

7. Research on the tension in a cotton medium when introducing working bodies of machines into it

The system of equations used to describe the motion of a compressible porous cotton medium allows conclusions and justification for a structural formula of the form of:

$$\sigma=\left(A+BV^2\right)\rho^k, \tag{18}$$

describing the tension inside the medium under processing when the working body of the machine is introduced into it. For this, there are the following justifications.

The sought formula should contain such parameters of the processed raw material and the cotton-processing machine interacting with it that are easily recorded in experiments and have a clear physical meaning. In this case, in (18) V is the penetration rate of the working body, ρ is the density of the medium, and k is the exponent, which reflects the geometric shape of the working body and the degree of machining of its surface, as well as the velocity V of the working body.

The values of the coefficients A and B are some constants determined experimentally.

Naturally, structural formula (18) should also coincide with the experimental results.

To substantiate the proposed structure (18), let us turn to the system of equations (1), (2), and (3); here are such parameters of the raw material as the pressure p, the velocity v of the particles of the raw material, and the density ρ.

It should be noted that the value of the velocity v of the medium is not entirely convenient in processing and analysing experimental results. This is due to the fact that v is variable over the entire volume of the raw material in the form of a spatial velocity field. Moreover, it is difficult to record it experimentally.

Let us now consider equation (1) of the medium motion. For simplicity, it is assumed that the events under study in the medium occur in the close vicinity of the velocity v when it is minimal during deceleration on the surface of the working body.

Then it is assumable that in (1):

$$\frac{\partial v_{\min}}{\partial t}=0.$$

In addition, in (1) the value of p reflects the tension inside the continuous medium. If p is considered as the pressure from the surface of the working body on the cotton raw material, then the sign of p in (1) must be changed to the opposite. In view of all the above, (1) will take the form of:

$$v\frac{\partial v}{\partial x}=\frac{1}{\rho}\frac{\partial p}{\partial x}, \tag{19}$$

where it must be assumed that the values of p and ρ reach the maximum values $p_{\max}$ and $\rho_{\max}$ with $v_{\min}$. Otherwise, (19) looks like this:

$$\partial p=\rho v\partial v. \tag{20}$$

The integration of (20) leads to:

$$p=\frac{\rho v^2}{2}+\text{const}, \tag{21}$$

where the integration constant const=p_0 is the initial value of the pressure inside the medium away from the surface of the working body.

Let us further turn to the continuity equation (2). As for the previous equation (1), it is assumed that here when the working body is introduced into the medium, the medium is compacted on its surface due to the fact that air is squeezed out of the interfibre space.

Then for the close vicinity of the studied events where $\rho=\rho_{\min}$, in (2):

$$\frac{\partial \rho_{\max}}{\partial t}=0,$$

and (2) takes the form of:

$$\frac{\partial}{\partial x}(\rho v)=0. \tag{22}$$

The integration of (22) results in:

$$\rho v=\text{const}, \tag{23}$$

where const=$\rho_0 v_0$ for a raw material point away from the working body.

From the processing of the experimental data it follows that the density ρ when decelerating the raw material at the surface can reach a value from $\rho^{1.5}$ to ρ^3 depending on the external shape of the working body and the degree of smoothness or roughness of its surface treatment, as well as the velocity V of introducing the working body.

Under these conditions, (23) will look as:

$$\rho^{(1.5-3)} v=\rho_0 v_0, \tag{24}$$

and, accordingly, (25):

$$p=\frac{\rho^{(1.5-3)} v^2}{2}+p_0. \tag{26}$$

It is noteworthy that an increase in the density of the raw material from the value of $\rho^{1.5}$ to ρ^3 on the surface of the working body is a direct source of damage to the fibres of cotton seeds and other defects in the raw material. Thus, based on the appearance of (24), (25), as well as the analysis of experimental data carried out in this work, it is possible to substantiate the formula of (19),

$$\sigma=\left(A+BV^2\right)\rho^k,$$

as a basis for calculating stress σ in the cotton medium on the surface of the working body of the cotton gin.

It is obvious that there is a direct relationship between the stress in the medium σ on the surface of the working body and the amount of damage to the cotton fibres and seeds, as well as other medium defects.

8. Discussion of the results of the study of the dynamics of the impact produced by the working bodies of the machines of a cotton processing unit on the quality of raw cotton

The theoretically and experimentally obtained results show that the speed of sound in a mixture of fibres and air is relatively low, compared to the speed of sound in linearly oriented fibres (filaments), where it is 1,700 m/s. With a raw material density of ρ=250–300 kg/m^3, the theoretically found speed of sound is 24–28 m/s, and the experimentally determined one is 50–60 m/s.

In the published works and studies [3, 5], insufficient attention was paid to analysing wave processes during cotton cleaning. The use of the theory of wave processes makes it possible to apply it to the description of shock processes when extracting impurities from cotton fibre, as well as to the study of the issue of internal movements of cotton seeds during the pressing.

The study of the dynamic conditions for the occurrence of vibrations during the rolling of an elastic particle of raw cotton on the working surfaces of the cleaners makes it possible to give recommendations on avoiding the appearance of undesirable soft defects in the raw material.

It is known that technological approaches to the primary processing of cotton entail speed limits imposed on the introduction of working parts of the machines into the raw materials.

These limitations were revealed by the empirical experience of processing a large number of raw materials with various properties of fibres, moisture, density, etc.

Thus, for example, splitting pack pickers are introduced into the cotton mass at a speed of V=3–8 m/s. The speed of impact of cotton particles on the grates of the cleaning machine can be V=10–12 m/s.

When cotton raw materials are transported by air through the pipeline system, inevitable impacts of cotton particles against the walls of the system occur.

The obtained unsatisfactory answer for the magnitude of the speed of sound at low densities of the raw medium is due to the same considerations as in the first case studied for high densities. The dynamic influence of the air included in the medium can be ignored.

It is noteworthy that there are still a number of questions which are hardly researched in the field of the dynamics of the impact produced by the working bodies of the machines of cotton processing units on cotton raw materials.

One of these issues is currently related to the permissible dynamic loads and the density of the raw material. The relationship between the density of porous raw materials and the range of changes in the dynamic loads has not been described in sufficient detail.

The development of this study consists in studying the process of introducing the working bodies of machines into a solid mass of raw materials at a speed commensurate with the speed of sound. It is likely to imply a significant increase in the pressure, density, and temperature on the surface of the working bodies and adjacent areas of a continuous mass of the raw material. This is due to the well-known compressibility effect for the transonic motion of solids in a continuous compressible medium.

However, a significant increase in the pressure, density, and temperature in the processed raw materials can be a source of significant damage to cotton fibres.

9. Conclusions

1. The analysis of the results obtained for the speed of sound in a cotton mass shows that the speed in a two-component medium further sharply decreases in its value even with an insignificant amount of cotton fibre in the mixture.

Thus, with a fibre content of 5 kg in 1 m^3 of the mixture, the speed of sound is s=150 m/s, and with a fibre content of 25 kg in 1 m^3 of the mixture, the speed of sound is already s=73 m/s. The minimum value of s is in the range of s=21–24 m/s for a wide range of raw material densities ρ=300–900 kg/m^3.

2. When assigning a technological mode of processing, it is necessary to comply it with the value of the sound speed for a given density of the raw material. It is necessary to avoid such rates of penetration of the working bodies into the raw material that are commensurate with the speed of sound at a given raw material density.

3. On the basis of the experimentally determined value of the dynamic compressibility of cotton of different weight densities, the relationship between the density, the rate of external loading, and the internal tension in the medium was

revealed and formulated. Moreover, the vibration frequencies of the cotton medium were determined as a function of density as well as the speed of sound waves.

4. Based on the generalization of experimental studies of the raw cotton compressibility, a correlation was obtained for the dynamic state of the raw material, linking the stress in the medium σ kg/cm^2 with the weight density of the medium ρ kg/m^3 and the velocity of introducing the working body V m/s. The ratio was determined for the density range of $\rho=130-260$ kg/m^3.

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