There is a large body of theoretical and experimental research aimed at determining the warp thread deformation and tension. Analytical solutions and mathematical models of the stressed state of the warp and weft threads in the formation of fabric were proposed. In almost all studies, the deformation of the warp thread was determined separately when shedding and beating the weft. There is an experimental method for determining the deformation of warp threads, which makes it possible to eliminate some of the shortcomings inherent in the theoretical techniques. However, that method has some drawbacks, such as the low accuracy of strain measurement and the complexity of certain measuring operations, which leads to an increase in the time spent on the experiment.

This paper reports a study that addresses those shortcomings by proposing to photograph the object being measured using a digital camera connected to a computer system to print the image. An electronic caliper that is used to measure the deformation of warp threads on printing paper takes into consideration a fraction of a millimeter when measuring.

The proposed method makes it possible to determine with sufficient accuracy and speed the deformation of warp threads in the elastic feed system of the loom, as well as allows visual control over the changes in the deformation of warp threads in the machine. The use of this method makes it possible to reduce the time of measuring the deformation of one thread from 30–40 seconds to 5–7 seconds, which is 5–6 times less than that in the existing one and provides measurement accuracy to at least one dozen mm.

The results of this work could be applied to determine the warp thread deformation and tension on looms when making the main weave fabrics in order to reduce the uneven tension of the main threads, increase labor productivity, and improve the quality of the fabric

Keywords: warp threads, thread deformation, tension, elastic feed system, loom

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EXPERIMENTAL METHOD FOR DETERMINING THE DEFORMATION OF WARP THREADS ON LOOMS

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1. Introduction

Increasing the productivity of labor and equipment and improving the quality of products in the weaving industry is an important task facing engineering and technical personnel and scientists in this field. One of the ways to radically solve this issue is to decrease equipment downtime and reduce the breakage of the warp and weft threads. The main reason for the breakage is the state of the equipment and the technological process of weaving, which are largely related to the tension and deformation of the warp and weft threads. Therefore, one of the important tasks of theoretical and experimental research in the field of weaving is the study of the deformation and tension of warp threads and fabric in the elastic feed system of the loom, which is still relevant.

There are many solutions for determining the deformation and calculating the tension of warp threads. One of the first studies [1], which laid the foundations for the calculation of cyclic deformation and tension of warp threads, became the impetus for the development of this issue. After that, interest in this issue increased with the number of theoretical and experimental scientific studies increased dramatically. Most of the research explored the deformation and tension of warp threads in the manufacture of single-layer fabrics of the main weave on classical looms.

The range of fabrics and woven products for mass consumption that meets the modern requirements of consumers is expanding; new equipment for the production of these fabrics is being designed; existing equipment for making these fabrics is being improved. Technical fabrics have emerged, used in almost all fields of technology, in agriculture, in road construction, etc. [2], which are produced on appropriate looms. In the formation of all these fabrics on looms, the most important are the processes performed by the mechanisms of release and tension of the warp and removal of the fabric. These mechanisms' operations are strictly coordinated depending on the deformation and tension of the main and weft threads and fabric, that is on the feed, as well as the parameters of the fabric, and the design of the mechanisms themselves, which have a great influence on the structure and properties of the fabrics produced.

Thus, it should be noted that one of the most important tasks of theoretical and experimental research in the field of weaving is to study the deformation and tension of warp threads and fabric in the elastic feed system. Therefore, it is a relevant task to examine the theory and experimental methods for studying the stressed-strained state of the elastic system of threads in a loom.

2. Literature review and problem statement

The issues related to studying the deformation and tension of warp threads have been tackled in many studies, among which the fundamental work [1] deserves great attention; it underlies the foundations of methods for solving this issue. It was noted that the nature of change in the deformation and tension of threads is cyclic in the longitudinal direction of the elastic feed system of the loom. It is shown that not only the length of the warp in the zone of the edge of the fabric to the point of descent of the warp from the beam is subjected to stretching deformation but also a certain length of the warp on the beam. The author called this length equivalent and proposed theoretical formulas to determine it. It should be noted that when deriving that formula, the adhesion of the thread with the winding of the beam and the tension of threads in the winding of the beam were not taken into consideration, which led to some inaccuracies in the calculations.

In [2], an analytical expression in the form of a trigonometric polynomial was proposed to determine the magnitude of the cyclic deformation of warp threads during shedding over a single revolution of the main shaft. It is noted that the accuracy of the calculation result depends on the number of terms in the polynomial.

However, the proposed formulas in the form of a trigonometric polynomial obtained from the diagram of the movement of remises, make it possible to determine the cyclic deformation during shedding. Therefore, these formulas do not reflect the magnitude of the total deformation of the elastic feed system of the loom.

In [3], the property of the elastic feed system of the loom was studied; it was proposed to take, as a characteristic of the elastic properties of textile materials, the stiffness coefficients of the warp and fabric threads, determined under conditions of short-term deformations. It is proposed to use, to calculate the tension of the thread, not the modulus of elasticity but the coefficient of stiffness at stretching. However, it should be emphasized that the use of the stiffness coefficient in calculating tension for certain types of threads and materials from them that obey Hooke's law is impractical. Otherwise, the results expected from the calculation may not be accurate.

Paper [4] refines the formula reported in [1] for determining the equivalent length, taking into consideration the adhesion of the thread to the winding of the beam and the tension of threads in the winding of the beam. In [4], it is noted that calculations based on the formula from [1], in comparison with the refined formula, produce an overestimated result, by more than 3 times. The parameters of feeding the loom were optimized, taking as an optimization criterion the total work of deformation of the warp threads due to the beating of the weft. A formula was derived for an additional deformation of the warp thread on the beam caused by a tension increment equal to the difference between the tension of the element at additional deformation and the tension of the thread in the beam winding. However, the cited paper lacks data on the magnitude of the deformation of warp threads during shedding and the working area of the fabric, which are one of the components in the general deformation of the elastic feed system.

A series of theoretical and experimental studies were carried out to investigate the parameters of the elastic feed system on different looms with various variants of the position of the backrest on the machines in the manufacture of various fabrics according to the raw material composition, and the interweaving of fabrics. In [5], the stressed-strained state of the warp thread along the width of the feed on the STB-2-216 loom under dynamic conditions in the phases of intercession, standing, beating over a cycle of operation was experimentally investigated. Based on the data obtained, the authors constructed diagrams of changes in the tension of warp threads at the time of entry, at the time of beating, at the time of standing depending on the width of the loom; the study's result identified zones with the largest and least tension of the thread, which should be taken into consideration when setting up the equipment. The cited work did not address issues related to deformation and its relationship with the tension of warp threads. In addition, the reported results are valid only for the conditions under which the experiment was conducted.

The issues of changing the deformation and tension of warp threads on looms with friction main regulators were considered in paper [6], which describes the parameters that change as the warp descends from the beam. The analysis of the influence of the changing parameters of the regulator on the change in the tension of threads during the descent of the entire warp from the beam, affecting the static component of the tension of the main threads, is given. A calculation procedure was devised for determining the static tension of the main threads on shuttle-free looms of the STB type, equipped with friction main regulators. The calculations of the static component of the tension of the main threads under various parameters for the conditions of production of fabrics with different densities on the weft made it possible to assess the effect of the parameters on the stability of the tension of threads. The cited work did not separately consider the deformation of the warp threads in certain sections of the feed line of the elastic loom system, although it is closely related to tension.

Paper [7] reports analytical and experimental analyses of the deformation and tension of warp threads in the upper and lower branches of shedding during the production of linen weave fabric on the STB loom depending on the position of the backrest. As a result of the study, it was found that when the backrest is placed above the level of the breast beam, the deformation and tension of the threads in the upper branch of shedding is lower than that of the threads in the lower branch. It is argued that during beating and shedding the main threads of the upper branch of the shed are 2 times different from the amounts of tension during beating and shedding involving the main threads of the lower branch. In that case, the amount of deformation during shedding was calculated based on the size of the shed on each remise. It should be noted that the cited work does not define the deformation and tension of the main threads in other areas of the elastic feed system. Data on the total deformation of the elastic feed system of the loom are not given.

In [8], a theoretical study was carried out to build a mathematical model of the intensity of the formation of a new fabric element on looms with an additional backrest. In the cited work, the total work of tensile deformation due to beating is taken as the optimization criterion; a refined formula for the total work of the deformation of the warp due to beating on looms with additional backrest when using lease rods was derived. The dependence of the increment of tension of the warp thread due to beating for the zone of the backrest-lease rod was established. However, it should be emphasized that the cited work lacks estimation data for quantitative assessment, confirming the study's theoretical results.

The authors of [9] performed a mathematical analysis of the deformation of the main threads on looms with a positive main regulator to study the influence of the position of the swinging backrest on the tension of the thread. They derived formulas for determining the deformation of warp threads in separate sections of the feed line of the loom at different variants of the position of the swinging backrest. A formula for calculating the tension and relative deformation of warp threads is given. At the same time, unlike previous works, instead of the stiffness coefficient of warp threads, the Young modulus was used. The cited work has the same drawbacks as [8].

One of the issues of modeling the tension of the warp is tackled in paper [10], which reports a systematic analysis of modern looms, which made it possible to build a suitable simulation model for calculating the tension of the warp. An improved model combined with a genetic algorithm and a gradient-based method was used to calculate the optimal feed parameters for the weaving process. The application of a genetic algorithm or a gradient-based method makes it possible to optimize the parameters of the loom. Using the optimized setting parameters for the loom showed that the quality of the fabrics produced could be improved. Further analysis of the fabrics did not show the effect of the optimized parameters of the loom on the mechanical properties or performance of the weaving process. The simulation did not take into consideration the cyclical nature of the change in the deformation and tension of main threads when shedding and beating the weft on the loom, which leads to a decrease in the amount of tension.

Experimental studies were carried out in [11] to determine the tension of the main threads by the method of experiment planning, taking into consideration the types of processed raw materials and the design of machine tools. The reported results could be used to optimize the technological process of weaving in optimizing the structural features of the corresponding parts of the loom, reducing the number of yarn breaks, and improving the quality of manufactured fabrics. The cited work does not take into consideration the stiffness of the bending of threads, the nonlinearity of the change in friction forces on the value of the normal pressure, the real angle of coverage of the thread by the guide thread, and the angle of radial coverage of the thread by the surface of the guide.

Those factors were taken into consideration in work [12] that reports studies to determine the tension of threads when interacting with the guides and working bodies of looms and knitting machines having the shape of a torus. As a result of experimental studies, regression dependences were built to determine the joint action of the tension of the thread before entering the guide, the ratio of the radius of the inner circle to the radius of the working circle and the rated value of the contact angle by tension behind the guide. The reported results and their application make it possible to optimize the process of yarn production using the considered technological equipment by minimizing the tension of the thread in a working area.

Of interest is work [13], which considers a study on the computer implementation of the algorithm for determining the tension of the thread on a loom and a circular knitting machine using recursion; its computer implementation was shown. Experimental studies were carried out to determine the joint effect of the tension of the driven branch of the thread, the radius of the guide, and the calculated value of the angle of coverage, on the tension of the leading branch of the thread. The cited work planned and implemented a second-order orthogonal plan for three factors. The cited study confirmed the possibility of using recursion in the sequential determination of tension in the zones of technological equipment from the entrance zone to the zone of fabric and knitwear formation.

It should be emphasized that those issues were considered for looms in the manufacture of single-layer fabrics of the main weave. In contrast, paper [14] reports a study to investigate those issues for loop fabrics when using the STBM-180 machine (OAO «Textilmash», Russia). It analyzes the stressed-strained state of the elastic feed system of the root and loop main threads and proposes a method for calculating the tension of these threads depending on the type of weaving of the fabric soil and the technological parameters of the feed of the loom. Mathematical models were built followed by the subsequent optimization by the method of canonical transformation of the optimal technological parameters of the production of loop fabric with minimal values of tension of the threads of the root and loop warp. However, the experiment conducted to confirm the proposed methodology for calculating the deformations and tensions of warp threads was not carried out on all sections of the elastic feed system.

As a technical solution to the problem of determining the deformation of threads in the feed of the loom, a device was proposed in [15]. The result is achieved by taking into consideration the movements of warp threads, which are registered by tensor sensors connected to a freely rotating backrest. As a result, it becomes possible to acquire information about the change in the longitudinal deformation of the feed of the loom. However, there is no specific information on the use of that solution in practice.

It should be noted that almost all studies determine the deformation of warp threads of the elastic feed system of the loom either theoretically or based on the value of tension and the coefficient of stiffness of the threads. Only [16] suggests an experimental method for determining the deformation of warp threads of the elastic feed system, the essence of which is as follows. On the surface of the beam winding, two parallel lines are drawn with the initial distance l. As the warp threads move to the edge of the fabric under the action of tensile forces, elongation occurs, as a result of which the distance l, increasing, acquires the value L on individual threads. Dividing the difference $L-l$ by the distance between the beam and the edge of the fabric, taking into consideration the length of the deformed part of the warp on the beam, the deformation of warp threads arising in this zone is determined. The distance l on the individual threads of the warp is measured with a millimeter ruler directly on the loom.

An experimental test of the proposed method was carried out in the manufacture of cotton fabric of satin weave on a Toyota loom (Japan) [17]. The results of the experiment confirmed the possibility of its successful application to determine the amount of deformation in any zone of the elastic feed system of the loom.

Measuring the distance L between the points on warp threads with a millimeter ruler does not allow for accurate accounting of fractions of a millimeter, which led to a decrease in the accuracy of the experiment.

Picking up individual threads, keeping them in a tensed state and measuring the distances between points is not convenient, and it takes a lot of time.

Thus, there is an unresolved issue related to the application of a more practical method for determining the deformation of warp threads of the elastic feed system on looms with increased accuracy.

3. The aim and objectives of the study

The aim of this work is to assess the possibility of applying an experimental method for determining the deformation of warp threads of the elastic feed system on looms to achieve increased accuracy.

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

– to improve the existing experimental procedure for determining the deformation of warp threads of elastic feed systems;

– to determine the amount of deformation of warp threads of the elastic feed system;

– to determine the tension of warp threads on the loom.

4. The study materials and methods

4. 1. Materials

The following materials were used in this study.

The pneumatic loom Pıcanol Ominplus-Summum (Belgium), cotton fabric of linen weave, the camera Canon EOS M200 (Japan) – for taking pictures of the measured object, the HP computer, the Canon printer MF 3010 (Japan) – for printing images. An electronic caliper (Digital Caliper, made in Ukraine). To acquire images of all the photographed objects in one position, a special original device for setting and adjusting the position of the camera was used.

The main parameters of the loom necessary to perform the work are as follows: the width of the feed is 1,800 cm; the speed of the main shaft is 700 min^{-1}; the number of remises is 4; the diameter of the beam winding is 600 mm; the estimation length of warp in the feed, taking into consideration the equivalent length, is 1,850 mm; the estimation length of the fabric in the feed of the loom is 1,500 mm.

The values of the fabric parameters: fabric weave – linen; the width of the harsh fabric is 235 cm; the feed width of the warp – 254 cm; the linear density of the warp is 20 tex; the linear density of the weft is 20 tex; the number of threads of the warp in the feed is 5,410; the density of warp threads per 10 cm is 200; the density of threads per 10 cm is 220; the allowance of the warp is 6.83 %; the shrinkage of the weft is 6.2 %.

The main and weft threads are made by a pneumatic mechanical spinning method.

4. 2. Research methods for determining the deformation of warp threads of the elastic system

When performing this work, an experimental method for determining the deformation of warp threads, proposed in [16], was taken as a basis. To enhance the accuracy of the experiment, a method for measuring the elongation of warp threads in the elastic feed system was improved. The experimental data were treated, and the mathematical models were constructed, by employing the software EXCEL (Microsoft Corp., USA). To calculate the deformation, well-known formulas from the reference literature on weaving and textile materials science were used.

The experiment was carried out at the weaving enterprise «Textile Park Gilan» (Sumgait) on the loom «Picanol», in the production of cotton fabric calico Creton.

5. Results of investigating an experimental method for determining the deformation of warp threads on looms

5. 1. Improving the experimental method for determining the deformation of warp threads and its implementation

The use of a millimeter ruler for measuring distances, involved in the previously developed method [16], does not make it possible to take into consideration the fractions of a millimeter, which would entail a decrease in the accuracy of the measurement. Another disadvantage of this method is the complexity of some operations in measurement, which leads to an increase in the time spent on the experiment.

To eliminate these shortcomings, the following is proposed: to measure the distances *l* and *L* on paper with a photograph of the measured areas, taken with a digital camera and printed on a printer with an enlarged scale of the true value at least by three times. To measure distances, use a caliper.

Experiments have been carried out to compare the time taken to measure the distance *L* per one thread of the wart by existing and proposed methods. It was found that measuring this distance with a millimeter ruler per one thread took an average of 30–40 seconds, depending on the measuring location on the loom. This time includes the period spent on selecting and keeping each thread in a tensed state, as well as the measurement itself. And when the proposed method is applied, the time spent on measurement is only 5–7 seconds. This time consists of the period for photographing the objects of measurement, printing out the snapshots using a printer, and measuring them with a caliper on the paper.

When measuring distance *L*, the measurement accuracy is estimated in the range of one millimeter. In the case of using a millimeter ruler, it is possible to measure with an accuracy of 0.3–0.5 mm approximately, depending on the experience of the operator performing this work. The use of an electronic caliper provides for accuracy of up to one dozen mm.

Another important feature of the proposed method is the ability to control the results of the obtained data on all measurements and, if necessary, repeat the measurements of earlier experiments. Under a current method, traces of previous experiments on the loom disappear and it becomes impossible to verify the data.

To implement the proposed technique, a thin helium pen was used to draw on the surface of the beam with a diameter of 600 mm the parallel straight lines *ab* and *cd* with an initial distance *l* equal to 50 mm between them (Fig. 1, *a*). To study the change in the deformation of warp threads along the width of the feed, six sections with a width of 1 cm per 24 threads (6 rapports of weaving on the warp) were identified; photographs of these areas were taken.

To determine the deformation of warp threads in the zone of the free part, that is in the area between the beam and the edge of the fabric, the loom is turned on and warp threads 2, wound from beam 1, skirting backrest 3, move into the working area of the loom. In this case, under the action of tensile forces, the threads are elongated, as a result of which the initial distance *l* between the straight lines *ab* and *cd* increases and reaches the value *L*. In this case, points 4 on the warp threads form a wave-like shape (Fig. 1, *b*). When points 4 approach the edge of fabric 6, the loom stops, the warp threads are moved to the intercession phase position, and then the selected areas located between bird 5 and the edge of fabric 6 are photographed. After that, the photos are printed out.

Fig. 2 shows the samples of photographs of lines on the surface of the beam, on the warp threads at the edge of the fabric, and on the surface of the fabric near the crush roll.

When determining the deformation of warp threads in the working area of the fabric, the loom was turned on. When the points crossed the edges of the fabric by 5–6 cm, the loom was disabled to photograph the positions of the points on the surface of the fabric. These operations were repeated at the commodity roller to photograph the positions of the points.

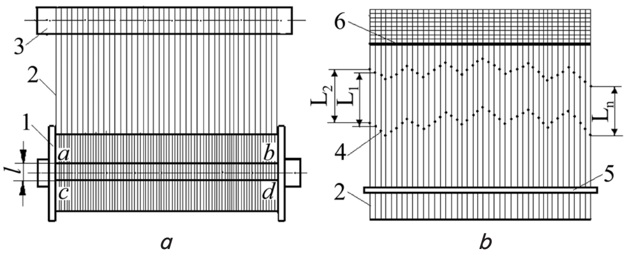

Fig. 1. Scheme for determining the deformation of warp threads in an elastic feed system on a loom: *a* – initial lines on the surface of the beam; *b* – the position of the points of straight lines on the warp threads at the edge of the fabric

Fig. 2. Samples of the printed-out photographs: *a* – on the surface of the beam; *b* – on warp threads; *c* – on the surface of the fabric

Then, after processing the data of the measurement results, the deformations of the warp threads in the free part zone and in the working area of the fabric of the elastic feed system of the loom were calculated. The experiment was repeated three times. The deformation of warp threads in any part of the elastic system is determined by the difference between the elongated and initial lengths L–l. When using the proposed method, these lengths on printed paper increased three times, therefore, the initial distance increased from 50 mm to 150 mm. In this case, the deformation of the warp threads is to be calculated on the basis of data taken from the paper. In this case, the amount of deformation would be increased as many times as the distance on the paper is increased.

Therefore, to determine the deformation of warp threads according to these data, it is possible to use the proportionality coefficient determined from the following formula:

$$C_p = l_{\ddot{o}} / l, \tag{1}$$

where C_p is the proportionality coefficient; $l_{\ddot{o}}$ is the reference distance on paper; l is the reference distance on the beam.

At $l_{\ddot{o}}$=150 mm and l=50 mm, the proportionality coefficient would be C_p=3. Therefore, in order to determine the true value of the deformation of warp threads, the resulting strain value on the paper must be divided by C_p.

Given this, the amount of deformation of the warp threads in the free part of the elastic system is to be calculated from the following formula:

$$\bar{\lambda}_{Oi} = \left(\bar{L}_i - l\right) / C_p, \tag{2}$$

where $\bar{\lambda}_{Oi}$ is the average deformation of one thread of individual sections, mm; $\bar{L}_i$ is the average distance between the upper and lower points (Fig. 1, *b*) on one thread on the printed paper, mm. The average distance $\bar{L}_i$ is the average value of 10 measurements.

Then the amount of deformation per one meter of the warp thread is calculated:

$$\bar{\lambda}_{O_M} = \bar{\lambda}_{Oi} 1{,}000 / l_e, \tag{3}$$

where l_e is the estimated length of the warp, equal to 1,850 mm, consisting of the length of the free part of the warp threads (1,200 mm) and the equivalent length (650 mm with a winding radius of 300 mm).

The equivalent length of warp threads on the beam is calculated from the formula given in [1].

To determine the amount of deformation of the main threads in the working area of the fabric in the elastic feed system, the following formula can be used:

$$\bar{\lambda}_{OT_i} = \left(\bar{L}_{OT_i} - \bar{L}_{OT}\right) / C_p, \tag{4}$$

where $\bar{L}_{OT_i}$ is the average distance between two points on each thread of the warp in separate areas of the fabric near the crush roll; $\bar{L}_{OT}$ is the average value of the initial distance between two points on each thread of the warp in separate areas of the fabric at its edge.

The initial distance $\bar{L}_{OT_i}$ on each section of the fabric takes a different value since the deformation of warp threads in the fabric is a continuation of the deformation process of these same threads in the free part of the elastic feed system. Therefore, the initial distance on each section of the fabric is to be calculated from the following formula:

$$\bar{L}_{OT} = \bar{L}_i\left(1 - 0.01a_o\right),$$

where a_o is the allowance of the warp in the fabric. For a given fabric, a_o=6.83 %.

Substituting values $\bar{L}_{OT_i}$ in (4) produces the average deformation of warp threads of the individual areas in the working area of the fabric:

$$\bar{\lambda}_{OT_i} = \left[\bar{L}_{OT_i} - \bar{L}_i\left(l_{TP}\left(1 - 0.01a_o\right)\right)\right] / C_p. \tag{5}$$

Then the amount of deformation per one meter of the warp threads in the working area of the fabric was determined:

$$\bar{\lambda}_{OT_M} = \bar{\lambda}_{Ot} 1{,}000 / l_{TO} = 1{,}000 \bar{\lambda}_{Ot} / \left[l_{Tp} / \left(1 - 0.01a_o\right)\right], \tag{6}$$

where l_{TO} is the length of the warp in the working area of the fabric; l_{Tp} is the length of the fabric in working area, that is the length of the fabric between the edge and the crush roll. At l_{Tp}=1,500 mm and a_o=6.83 %, the length of the warp in the working area of the fabric l_{TO} is 1,610 mm.

After that, the total (overall) deformation of warp threads in the elastic feed system of the loom was determined from the following formulas:

– for the estimated length of the warp in the elastic feed system:

$$\bar{\lambda}_{OC} = \bar{\lambda}_O + \bar{\lambda}_{OT}; \tag{7}$$

– per meter of the warp in the elastic feed system:

$$\bar{\lambda}_{OC_M} = \bar{\lambda}_{O_M} + \bar{\lambda}_{OT_M}. \tag{8}$$

The experiments were repeated three times, so for each site 3×10=30 measurements of the distances L_i, L_{OTi} and L_{TO} were carried out; their average values were determined.

Based on this data, the average $\bar{L}_i$, $\bar{L}_{OT_i}$, $\bar{L}_{OT}$ values were calculated.

It should be noted that this method could also be used to determine the amount of fabric deformation in an elastic loom feed system by using (4). However, in this case, the initial distance between the points on warp threads along the width of the fabric at its edge would not be constant. For this reason, there could be small deviations in the deformation of the fabric along its width. This drawback can be eliminated by creating a condition for the constancy of the initial distance on the surface at the edge of the fabric, which requires a detailed study.

5. 2. Results of the study on determining the deformation of warp threads in an elastic feed system

Data on the deformation of the main threads, calculated from (2) and (5) depending on the width of the warp feed, are given in Table 1. For clarity, Table 1 shows the calculation formulas and the values of their parameters.

Table 1 demonstrates that a change in the deformation in both zones of the elastic feed system occurs in the same way. In the extreme areas of the warp and fabric, the amount of deformation is less than in the middle areas. The maximum value of deformation, 5.90 mm and 1.81 mm, is reached in the middle part of the feed width in the free part of the warp and working area of the fabric, respectively. The average value of the deformation of the main threads in the free part of the warp is 4.88 mm, which is 3.21 times greater than that in the working area of the fabric of the elastic fabric in the feed system, equal to 1.52 mm.

Formulas (3), (6) were used to calculate the average deformation values per meter of thread in the free part of the warp and in the working area of the fabric; formulas (7), (8) – the total deformations of the warp threads in both zones of the elastic feed system. The calculation results are given in Table 2.

Table 2 shows that the difference between the greatest and smallest deformations in the free part of warp threads is much greater than that in the working area of the fabric in the elastic feed system, which are 2.11 mm and 0.64 mm, respectively.

Based on the data from Table 2, the EXCEL software was used to construct plots of the change in the total deformation of warp threads along the width of the loom feed (Fig. 3).

Fig. 3 demonstrates that the nature of change in the deformation of warp threads, both in the free part and in the working area of the fabric in an elastic system, is similar for the width of the feed. The amount of the deformation of the warp, starting from the left-hand edge, slowly increases; in the middle areas, it acquires a maximum value; as it approaches the other edge, it begins to decrease. The greatest deformation of warp threads occurs at a feed width of 1,500 mm in both zones of the elastic feed system.

Table 1

Deformation values for the estimated length of threads in the zone of the free part of the warp and in the working area of the fabric in the elastic feed system at C_p=3

Warp feed width, mm	Deformation of the main threads of the free part in the elastic feed system, mm		Deformation of the main threads in the working area of the fabric, mm	
B	$(L_i - l)/C_p$	$\bar{\lambda}_{Oi}$	$[\bar{L}_{OT_i} - \bar{L}_i(l_{TP}(1-0.01a_o))]/C_p$	$\bar{\lambda}_{OT_i}$
5	(161.14–150)/3	3.71	(153.64–150.13)/3	1.17
50	(163.39–150)/3	4.64	(156.49–152.23)/3	1.42
100	(166.2–150)/3	5.40	(157.38–152.40)/3	1.66
150	(167.7–150)/3	5.90	(160.28–154.85)/3	1.81
200	(166.05–150)/3	5.35	(159.84–154.71)/3	1.71
250	(162.81–150)/3	4.27	(155.77–151.69)/3	1.36
Mean value		4.88	–	1.52

Table 2

Deformation of warp threads in an elastic system along the width of the feed

Width of loom feed, cm	The amount of deformation of the warp, mm					
	In the area of the warp in the elastic feed system		In the working area of the fabric in the elastic feed system		Total deformation of the warp of the elastic system	
	Per estimated warp length	Per warp meter	Per estimated fabric length	Per fabric meter	Per estimated feed length	Per warp meter
B	$\bar{\lambda}_{Oi}$	$\bar{\lambda}_{O_M}$	$\bar{\lambda}_{OT_i}$	$\bar{\lambda}_{OT_M}$	$\bar{\lambda}_{OC} = \bar{\lambda}_O + \bar{\lambda}_{OT}$	$\bar{\lambda}_{OC_M}$
5	3.79	2.05	1.17	0.73	4.96	2.78
50	4.64	2.51	1.42	0.88	6.06	3.39
100	5.40	2.92	1.66	1.12	7.01	4.14
150	5.90	3.14	1.81	1.10	7.71	4.24
200	5.35	2.89	1.71	1.04	7.06	3.93
250	4.27	2.31	1.36	0.82	5.63	3.13
Mean value	4.88	2.64	1.52	0.95	6.40	3.67

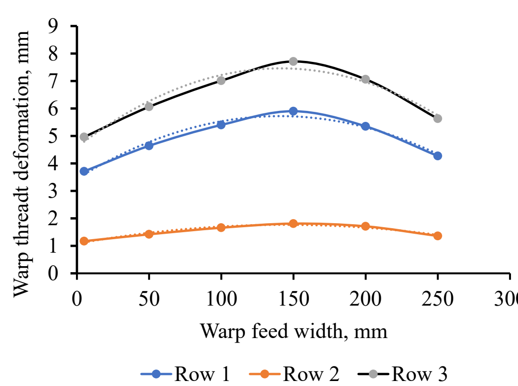

Fig. 3. Plots of change in the total deformation of warp threads in an elastic system along the width of the feed: Row 1 — deformation in the free part of the warp threads, Row 2 — deformation of the warp threads in the working area of the fabric, Row 3 — total deformation of warp threads

Fig. 3 shows that curve 2 that reflects the nature of change in the deformation of warp threads in the working area of the fabric has a smoother shape than curves 1 and 3. Obviously, this is due to the influence of the joint work of warp and weft threads in the formation and removal of fabric on the loom.

The EXCEL software was employed to derive the regression equations of these curves, as well as the coefficients of determination for the equations presented below.

For the free part of warp threads:

$$\bar{\lambda}_{Oi} = -0.0001B^2 + 0.0324B + 3.4423R^2 = 0.9732. \quad (9)$$

In the fabric's free zone:

$$\bar{\lambda}_{OT} = -3E - 0.5B^2 + 0.0095B + 1.0805R^2 = 0.9597. \quad (10)$$

The total deformation of the elastic feed system:

$$\bar{\lambda}_{OC} = -0.0001B^2 + 0.0406B + 4.5939R^2 = 0.9732. \quad (11)$$

Since the nature of change in the deformation of warp threads per one meter of the warp has the same character as the deformation in the free part of the elastic system, their plots are not given. The empirical formulas and coefficients of determination for defining the deformation of warp threads are given below.

In the free zone of the warp:

$$\bar{\lambda}_{O_M} = -3E - 0.5B^2 + 0.0095B + 1.0805R^2 = 0.9597. \quad (12)$$

In the fabric's working zone:

$$\bar{\lambda}_{OT_M} = -0.0001B^2 + 0.0312B + 3.5131R^2 = 0.9616. \quad (13)$$

Per warp meter in the elastic feed system:

$$\bar{\lambda}_{OC_M} = -9E - 0.5B^2 + 0.0235B + 2.719R^2 = 0.9881. \quad (14)$$

The coefficient of determination R^2 for equations (9) to (14) that characterizes the value of the approximation confidence turned out to be high, approaching unity, which confirms the high accuracy of the approximation and the proximity of the calculated values to the experimental ones.

5. 3. Results of the study to determine the tension of warp threads

To confirm the significance of the proposed method and to verify the correctness of the strain values of warp threads determined by this method for the fabric used in the experiment, the tensions of warp threads were calculated.

To calculate the tension of warp threads, a formula has been proposed in which one of the dominant parameters is the deformation of warp threads [1].

This formula is as follows:

$$F_o = \lambda_o C_o, \quad (15)$$

where C_o is the stiffness coefficient of a single thread of meter segments.

For basic medium-sized cotton yarn, (C_o=0.2 kg/cm [18]); λ_o is the amount of deformation per m of the warp in the elastic system.

When performing the calculation, the following values were taken in (15) instead of λ_o:

$\bar{\lambda}_{O_M} = 2.639\,\text{mm} = 0.264$ cm from Table 2.

$$F_o = \bar{\lambda}_{O_M} C_o = 0.264 \text{ cm} \times 200 \text{ cN/cm} = 52.8 \text{ cN}.$$

The total warp tension set in the control panel of the PICANOL loom is 3 kN. In this case, the tension of each thread is 55.45 cN (3,000/5,410 where 5,410 is the number of warp threads in the fabric). The difference between the calculated and actual values of the tension of warp threads is 55.45 cN–52.8 cN=2.65 cN, or 4.78 %.

This indicates that the values of the deformation of warp threads in the elastic system, determined by the proposed method, could be successfully used in determining the tension of warp threads on looms with an acceptable deviation.

Fig. 4 shows a plot of change in the tension of warp threads along the width of the feed of the loom. The tension values for the main threads, shown on the curve, are calculated from (15) for each region based on the $\bar{\lambda}_{O_M}$ values taken from Table 2.

The regression equation has been derived for the dependence of the tension of warp threads on the width of the feed of the loom, as well as the coefficient of determination R^2, given below:

$$F = -0.0118B^2 + 3.312B + 381.95R^2 = 0.9749. \quad (16)$$

A high value of the coefficient of determination R^2 confirms the reliability of model (16).

The plot in Fig. 4 demonstrates that the change in the tension of main threads along the width of the feed in the elastic system fits a parabolic relationship. The greatest tension of threads, 58.2 cN and 62.8 cN, is achieved in the middle sections, 100 cm and 150 cm, respectively. Moreover, the lowest value of the tension of warp threads is on the left-hand edge of the warp.

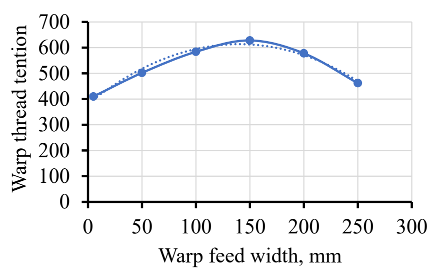

Fig. 4. Changing the tension of warp threads along the width of the feed in the elastic loom system

Similar results were reported in [19, 20] when studying the deformation and tension of warp threads on various looms in the production of fabrics from different raw materials and various weaves.

6. Discussion of results of the experimental study into the deformation of warp threads on looms

As a result of numerous theoretical and experimental studies, it has been established that one of the important issues affecting the efficiency of the weaving process and the quality of the fabrics produced is the creation of the necessary conditions for the normalization of the process of obtaining fabric on a loom. In solving this issue, an important role belongs to the cyclically-changing deformation and tension of warp threads in the elastic feed system of the loom, which was tackled in the theoretical and experimental work.

A procedure for determining the deformation of warp threads in the elastic feed system of a loom based on the method proposed in [14] has been devised, by improving the method of measuring the elongation of threads. The bottom line is that the measured section of warp threads on the loom is photographed using a digital camera connected to a computer system for printing out the image. To measure the elongation of warp threads on the printed paper, an electronic caliper is used.

Increasing the scale of the measured object by C_p times (2) (at least three times) contributes to improving the accuracy of measurements, owing to the use of photographing and printing out. At the same time, the use of an electronic caliper to measure the distance between the points on threads depicted on paper provides for a measurement accuracy of up to 0.01 mm. Whereas when using a millimeter ruler to measure this distance directly on the loom, as reported in [16, 17], it is possible to measure only with an accuracy of 0.3–0.5 mm, depending on the experience of the operator performing this work.

The experiment showed that when measuring the elongation of the thread by the proposed method, the measurement time is reduced by 5–6 times compared to the time given in [17], due to a reduction in the time spent on preparation for the measurement and on the actual measurement, which became possible by measurements in line with the proposed method.

As a result of experiments to determine the deformation of warp threads depending on the width of the feed, the data were acquired given in Tables 1, 2. Table 1 gives the average values of deformation in the free part of the warp and in the working area of the fabric in the elastic feed system, calculated from formulas (2) and (5). Table 1 shows that the average deformation of the main threads in the free part of the warp is 4.88 mm, and in the working area of the fabric – 1.52 mm, which is 3.21 times less than that in the free part of the elastic feed system. Based on the change in the deformation of warp threads in [21], it is noted that the deformations of warp threads in the working area of the fabric constitute only a small part of the total deformation of the warp of the elastic system, which largely confirms the correctness of the results of the experiment conducted in the current work. Table 2 gives the average values of deformation per one meter of the warp thread and the total deformation in the free part and in the working area of the elastic system fabric, calculated from formulas (3) and (6), (7) and (8), respectively.

Based on the data in Table 2, the plots of change in the total deformation of warp threads depending on the width of the feed of the loom (Fig. 3) were built. Fig. 3 shows that the nature of change in the deformation of warp threads in the free part and in the working area of the elastic system fabric is similar and nonlinear. At the same time, in the extreme areas of the warp and fabric, the amount of deformation of warp threads is less than that in the middle areas. Similar results were reported in [17] when using an existing similar methodology. In contrast to the results given in [17], where the values of the coefficients of determination in the empirical dependences between the deformation of warp threads and the feed width (for 2 fabrics) were 0.745 and 0.682, in this study, due to the increase in measurement accuracy, these indicators are 0.975–0.988.

To confirm the significance of the proposed method, the tension of the main threads is calculated from formula (14) given in [17]. In this case, the value of deformation per one *m* of the thread of the warp of the elastic system, obtained in this work, is used. As a result, it was found that the difference between the calculated and actual values of the tension of warp threads is 4.78 %. This indicates the reliability of the values of deformation of the warp threads determined by the proposed method, which could be successfully used in determining the tension of the main threads on looms with an allowable deviation. A plot of change in the tension of warp threads depending on the width of the feed of the loom has been constructed; the regression equation for this dependence was derived; the coefficient of determination R^2 with a value of 0.974 was defined.

One of the distinguishing features of this method is that its application could be useful for determining the deviations in the magnitude of deformations $\Delta\lambda$ of the individual threads of the warp relative to each other. To this end, it would suffice to measure the distances $\Delta_1, \Delta_2, \ldots \Delta_n$, which express the deviations of the deformations of individual threads relative to the first thread (Fig. 5). For example, the Δ_1 value shows the difference in the deformation that occurs between the first and second threads, the Δ_2 value – between the first and third threads, and so on.

Hence,

$$\Delta\lambda_1=\Delta_1-\Delta_2,\ \Delta\lambda_2=\Delta_1-\Delta_3, \ldots,\ \Delta\lambda_n=\Delta_n-\Delta_{(n-1)}.$$

However, this issue has not yet been practically resolved and requires further improvements.

Thus, the current study has confirmed the possibility of using the proposed method for determining the deformation of warp threads on looms. The study's results could be used to determine the deformation of warp threads on looms during the production of the main weave fabrics.

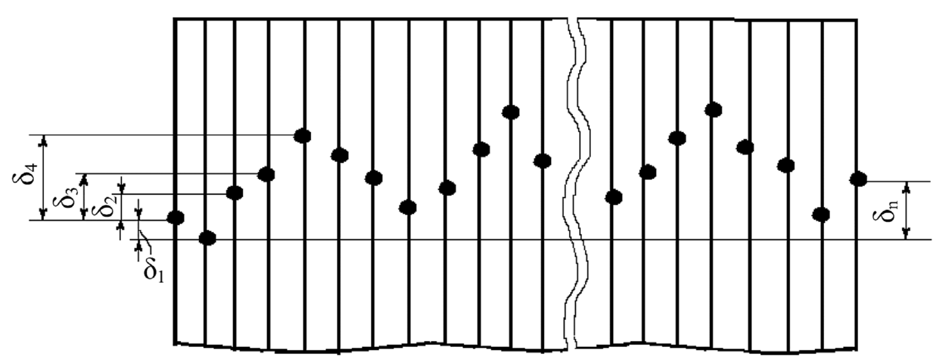

Fig. 5. Schematic representation of deviation in the deformation of main threads relative to each other

It should be noted that the study reported here was conducted only for one fabric article and in two zones of the elastic system of the loom. In addition, the measurement of the deformation of warp threads was carried out without taking into consideration the change in the radius of winding the beam. The application of the proposed method for determining the uneven distribution of deformation deviations on the warp threads along the width of the warp has not been finalized.

Promising issues are to devise technical measures for the application of the proposed method for determining the deformation of the fabrics of the main weave and to continue the study taking into consideration the above factors.

7. Conclusions

1. An experimental method for determining the deformation of warp threads on looms has been improved by improving the method of measuring the elongation of threads, which involves photographing the measured section of warp threads on the loom using a digital camera connected to a computer system for printing out the image. To measure the elongation of warp threads on printed paper, a caliper is used, which takes into consideration fractions of a millimeter when measuring. The use of this method makes it possible to reduce the time of measuring the deformation of one thread from 30–40 seconds to 5–7 seconds, which is 5–6 times less than that in the existing one and provides measurement accuracy to at least one dozen mm.

2. The deformation of threads in the zone of the free part of the warp and in the working area of the fabric in the elastic system along the width of the feed on the PICANOL loom in the production of cotton calico fabric was determined. It has been established that the nature of change in the deformation of warp threads along the width of the feed in the free part of the warp and the working area of the fabric in the elastic system is similar and parabolic. The maximum deformation of warp threads in both zones of the elastic system, 5.90 mm and 1.81 mm, respectively, is achieved in the middle of the feed. The average deformation of warp threads in the free part and in the working area of the elastic feed system is 4.88 mm and 1.52 mm, respectively. In the free zone, the deformation is 3.21 times greater than that in the working area of the fabric. Nonlinear regression equations have been derived for the dependence between the deformation value and the warp feed width with a high value of the coefficient of determination R^2.

3. The tension of warp threads is calculated using the deformation values based on the experiment, as well as the stiffness coefficient of the meter segment of the thread. It was found that the average tension of one warp thread is 52.8 cN, which is 2.65 cN (4.78 %) less than that set on the control panel of the loom. A nonlinear regression equation has been built for the dependence between the tension and width of the warp feed with a high value of the coefficient of determination R^2.

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