

Mathematical Modeling and Experimental Analysis of the Thread Take-up Function in Single-thread Chain Stitch Sewing Machines Type 101

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Abstract – An analytical and experimental methodology for evaluating functional characteristics of the single-thread chain stitch formation process (type 101) is proposed. The evaluation is based on degree of correspondence between the required and actual thread take-up, which reflects the machine's efficiency and the quality of stitch formation. A measuring system and an experimental procedure were developed to record thread take-up under different material thicknesses and stitch lengths. The obtained dependencies were approximated by sixth-degree polynomials with high accuracy ($R^2 > 0.99$), which made it possible to construct mathematical models of the thread take-up process. For GK-9 type machines, excessive thread take-up (20–64% above the required value) was set up, causing uneven thread tension and reduced stitch stability. The proposed methodology ensures quantitative evaluation, prediction, and regulation of thread take-up process, which improves functional efficiency of sewing machines and supports development of adaptive thread take-up control systems.

Index Terms — Analytical modeling, thread take-up function, chain stitch, adaptive control, sewing process, convergence function, technological parameters, thread take-up mechanism, mathematical modeling

I. INTRODUCTION

Modern trends in sewing and composite manufacturing highlight need to improve the stability and quality of stitch formation processes, especially

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under automated production conditions [1, 2]. As the operating speed of sewing machines increases and their functional tasks become more complex, the requirements for the ability of thread take-up mechanisms to provide required take-up for stable stitch formation without tension fluctuations also grow significantly. The inconsistency between required and actual thread take-up leads to stitch structure distortion, geometric deformation, and defects occurrence, which is particularly critical for composite reinforcement technologies.

The problem of stitch formation processes has been discussed in numerous studies devoted to the classification of stitches and the analysis of their structure [3–5], as well as to the optimization of thread consumption considering technological sewing parameters [6–10]. These studies laid the foundation for the analytical description of stitch formation processes and the defining patterns in interaction of working parts and mechanisms. However, being mostly focused on geometric and thread consumption models without an in-depth analysis of thread take-up kinematics in dynamics.

In studies [11, 12], the influence of technological parameters – stitch length t , zigzag width z , material thickness m , as well as stiffness and friction properties of materials – on formation process of multi-thread chain and shuttle stitches was established. At the same time, single-thread chain stitches are mostly considered from the standpoint of describing stitch formation process [12], without a quantitative assessment of the impact of technological parameters on stitch structure. The research presented in [13–18] confirmed feasibility of using the single-thread chain stitch type 101 for connecting and reinforcing layers of composite materials, where the simplicity of its structure and formation mechanism is combined with high process speed. Comparative studies [13–17] have shown that the stitch type 401 provides a uniform load distribution, whereas type 101 ensures lower thread consumption, simpler thread take-up function, and lower sensitivity to thread tension.

However, models [16–20] mainly focus on the influence of physical parameters of the material, such as thickness and presser foot pressure force, on thread tension and stitch structure stability. They describe thread consumption without the ability to track its actual take-up over time, which limits the prediction of how technological parameters affect stitch formation stability. This creates a significant

gap between theoretical calculations and the real operating conditions of high-speed sewing machines.

Further studies [21–28] have shown that the thread take-up functions actual $P(\varphi)$ and required $P'(\varphi)$ – are key characteristics of stitch formation process since the consistency between them determines stability of seam structure and quality of thread connection. For shuttle stitches type 301, these functions are presented in [21–23]; for single-thread stitches – in [24]; and for chain stitches of class 400 – in [25, 26]. However, systematic studies of the impact of parameters such as material thickness (m) and stitch length (t) on the shape of $P(\varphi)$ and $P'(\varphi)$ functions for single-thread chain stitch type 101 are still absent.

Developed methods for direct and indirect measurement of thread take-up [11, 20] allow to determine functional characteristics of take-up mechanisms, considering real properties of the thread. Nevertheless, the issue of take-up stability under varying technological conditions still is actual. Take-up control models proposed in [27] provided basis for the analytical evaluation of functional characteristics of sewing mechanisms, whereas recent studies [28–30] demonstrate transition to adaptive control systems that integrate intelligent algorithms and optimization methods (Kriging models, machine learning, multi-criteria regulation). Such systems provide automatic correction of thread take-up depending on material properties and stitch technological parameters in real time, opening up prospects for full automation of stitch formation processes. Implementation of this approach requires a mathematical description of the stitch formation process considering coordination of thread take-up functions.

Studies [31–35] are devoted to the processes of sewing composite preforms, where the stitch acts as a reinforcement element determining the strength and structural stability of the preform. Works [31–33] demonstrate impact of stitch parameters on the mechanical properties of multilayer systems, while [34, 35] substantiate the feasibility of using three-dimensional reinforcement of textile preforms by the stitching reinforcement method, which shares kinematic regularities with thread take-up process in sewing machines.

Design features of thread take-up mechanisms for type 101 stitches equipped with integrated thread take-uppers in kinematic link of the needle mechanism are discussed in detail in [36, 37]. Such mechanisms belong to systems with a simple kinematic chain [38] of slider or cam type with an elastic lever compensator. They potentially allow adaptive regulation of thread take-up depending on material properties, which is a key direction for next-generation high-speed sewing machines.

Therefore, literature analysis shows that despite the significant progress in theoretical models of stitch formation, the determination of actual and required thread take-up functions $P(\varphi)$ and $P'(\varphi)$ remains insufficiently studied. The lack of quantitative data about these functions complicates adjustment and regulation of thread take-up mechanisms. Thus, a comprehensive analysis of thread take-up functions for single-thread chain stitch type 101 is relevant, as it will help to improve the design of take-up mechanisms, enhance stitch formation stability, and ensure sewing quality during the production of composite preforms.

II. RESEARCH OBJECTS AND METHODS

The objects of research were mechanisms and processes of thread take-up for basic machines of the GK-9 design series (GK9-2, Gk9-10, GK9-18A, GK9-202, GK 9-500, GK9-801, Gk9-886, GK9-890C, GK-9000A), Gk26-1A, GK 35 (GK 35-8), GK-3700, KP3000, RG-900D (RZ-668, RG-555) [39, 40], which are widely used in light and food industry enterprises. As part of the study, the value of actual and required take-up functions was determined experimentally at minimum and maximum values of technological parameters (m , t) for GK-9-2 sewing machines.

In the specified types of machines, sliding type thread take-up mechanism [38] with one thread take-upper TU (Fig. 1) and system of thread guides G_i is used. The function of actual $P(\varphi)$ and required $P'(\varphi)$ take-up for this machine was determined experimentally using the method proposed in [11]. According to it, general thread take-up circuit G_0 -A (Fig. 1) is divided into “thread take-up circuit” – G_0 -N and a “thread consumption circuit” – N-A with shared point N, which corresponds to upper edge position of the needle eye at its uppermost position.

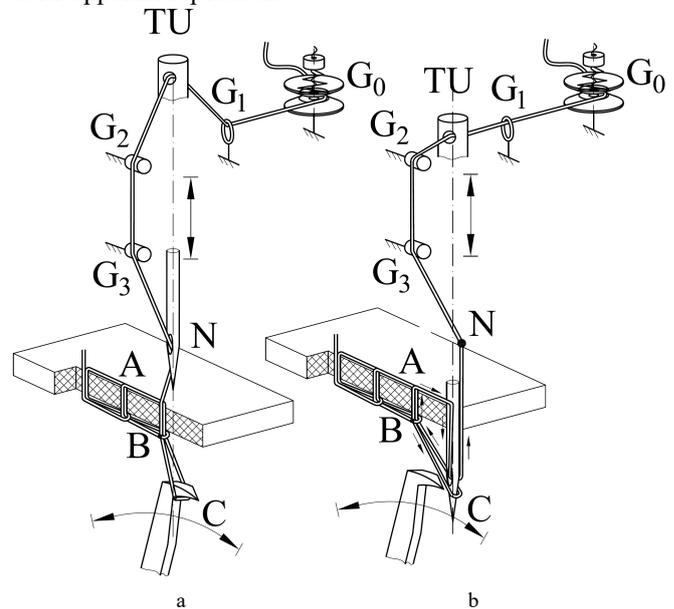
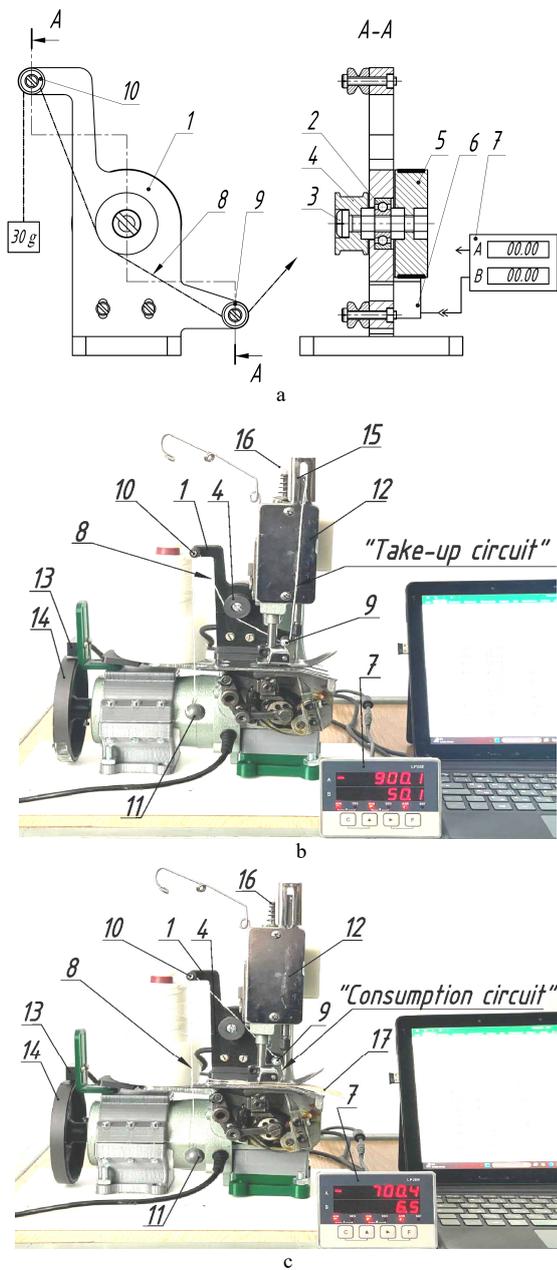


Fig. 1. Scheme of the general thread take-up circuit when forming a chain stitch type 101 in the GK-9-2 machine: a – general take-up circuit at the initial position, b – general thread take-up circuit at the “stab” moment of the previous thread loop and its descent from the expander nose

To measure thread “take-up circuit” (Fig. 2, a) was used device, developed at the Department of Mechanical Engineering. The device contains a body 1, in which a pulley 4 and a magnetic flywheel 5 are fixed in a bearing 2 on an axis 3. An induction sensor 6 is fixed next to the magnetic flywheel 5 to measure the circumference of the flywheel 5 during its rotation, and obtained values are displayed on a digital display 7 (digital channel B, Fig. 2). Rotational movement of the magnetic flywheel 5 was carried out due to the passage of the thread 8 in a loop wound on the pulley 4 in several turns, which provided reliable adhesion and eliminates slipping possibility. One free thread end passed through roller 9 and then gone to “take-up circuit” or “consumption circuit”, depending on reserch direction (Fig. 2, b and Fig. 2, c, respectively). The other thread end passed through the roller 10, and weight 11 was fixed to its end.

Rotation angle of the main shaft of GK-9-2 sewing

machine – 12 (Fig. 2, b, c) was measured using another induction sensor 13, which read rotation angle of the magnetic flywheel 14, and angle values were displayed on the digital display 7 (digital channel A, Fig. 2).



1 - device body; 2 - bearing; 3 - axis; 4 - pulley; 5, 14 - magnetic flywheel; 6, 13 - induction sensor; 7 - digital display; 8 - thread; 9, 10 - roller; 11 - weight; 12 - GK-9-2 sewing machine; 15 - thread take-upper; 16 - thread tension regulator; 17 - material

Fig. 2. Experimental setup for measuring values of thread take-up function of thread take-up circuit $P(\varphi)$ and $P'(\varphi)$: a – experimental setup structure; b – experimental setup for measuring values of the actual thread take-up function $P(\varphi)$; c – experimental setup for measuring values of the required thread take-up function $P'(\varphi)$

To minimize the influence of thread physical and mechanical properties during experiment, its parameters were approximated to the characteristics of an ideal thread [20]. This was achieved by fact that during device calibration and experiment itself, the same thread was used, and the force applied to it (weight of 30 g) remained unchanged in both cases. The experiment was carried out under the following conditions:

1. The needle produced by "Raly" company, model GK9,

№ 230, and cotton-paper thread 10S/3 left-hand twist in three folds were used in experiment. The material used in experiment was TLW "Obukhov" packaging cardboard [41], its compressed thickness under pressure foot force was: $m_{min}=0.4$ mm and $m_{max}=8$ mm.

2. To assess the minimum and maximum values of the required thread take-up, the study was conducted at the extreme values of the stitch technological parameters: $m_{min}=0.4$ mm, $t_{min}=8$ mm, $m_{max}=8$ mm, $t_{max}=12$ mm.

4. The actual stitch length was determined as the arithmetic average for 10 stitches length.

3. The regulator force was set in such a way to ensure chain stitch formation according to the specified technological parameters, which guaranteed the appropriate stitch structure [3].

To determine values of the actual thread take-up functions $P(\varphi)$, lengths changes in "take-up circuit" was done (Fig. 2, b). To achieve this, thread 8 was wound several times on pulley 4 surface to eliminate its slipping possibility. Thread 8 ends were passed through rollers 9 and 10, which are movable mounted on body 1. A weight of 30 g was fixed to one of the thread 8 ends, and the other one was wound to "take-up circuit" and thread take-upper 15. Machines main shaft position 12 was set at with 10° interval accordingly to indications of digital display 7 "A" channel by rotating the flywheel 14. In parallel, length changes in "take-up circuit" under the impact of weight 11 due thread take-upper 15 position changes were recorded on channel "B" of the same display.

The values of the required thread take-up functions $P'(\varphi)$ were obtained by measuring length changes of the "consumption circuit" (Fig. 2, c). Firstly, corresponding values of the technological parameters t and m were established and regulator 16 was set up to ensure a uniform stitch structure, free from defects (tightening, sagging, excessive tension of thread loops). The flywheel 14 was rotated with 10° interval additionally, accordingly to the technological process of type 101 stitch formation, measurements were carried out at characteristic moments of stitch formation process. For this purpose, a cyclogram of working bodies interactions for GK-9-2 machines was obtained, which parameters are given in Table 1.

TABLE 1

Characteristic moments of type 101 chain stitch formation process

Pos.	The physical essence of formation moments for single-thread chain stitch	Main shaft rotation angle
φ_{0-9}	The uppermost needle position and the rightmost expander position	0° (360°)
φ_1	End of material transportation	50°
φ_2	Needle eye passes in material	$95-68^\circ$
φ_3	Needle tip performs a "stab" of the previous thread loop and pulls it out of the expander nozzle.	172°
φ_4	Reducing the thread loop of thread take-upper	172°
φ_5	Needle downmost position	180°
φ_6	"Overlap loop" formation and capturing by the expander nozzle	255°
φ_7	Reducing "overlap loop" to the size of expander nozzle	255°
φ_8	Start of material movement	288°

At moments φ_{3-4} and φ_{6-7} , the “consumption circuit” was reduced to size limited by geometric parameters of working elements and their positions at the corresponding moments φ_4 , φ_7 and φ_8 . In the period φ_{5-6} , the indicators of the “consumption circuit” remain constant, that is required for stability of "overlap loop" formation process and corresponds to function $P(\varphi_5)$ value at argument φ_5 value. The "consumption circuit" length value and main shaft rotation angle were measured similarly to the measurement at the "take-up circuit".

Device 1 calibration (Fig. 3) was performed by measuring the ratio between pulley 2 and magnetic block 3 diameters. Series of measurements ($N=10$) was carried out in 0–50 mm range for this purpose. Thread 4, passing through pulley 2, under the impact of weight 5 moved magnetic tape 6. The movement of thread 4 through tape 6 was recorded by sensor 7 (channel A) of measuring device 8, while the movement of magnetic block 3 was determined by a separate sensor of device 1 (channel B).



Fig. 3. Calibration scheme of the experimental setup

The length readings of the “consumption circuit” and “take-up circuit” were processed in two stages. At the first stage, the results of direct measurements were processed, with calculation of average values and standard deviation for series of experiments at certain points (main shaft rotation angle, digital display readings in millimeters), according to the method [42, 43]. The results containing obvious gross mistakes, accordingly to the recommendations [44], were discarded, and the remaining values were processed further accordingly to the algorithm [45].

Before processing the results, all data were checked for anomalous values using the Chauvenet criterion, accordingly to the recommendations [42]. If such values were detected, they were removed from the calculation, and the remaining values were calculated repeatedly.

The following assumptions were considered:

1. Neglecting methodological fault;
2. Recognition that instrumental fault has only a systematic component;
3. Recognition of additional fault as a random component;
4. The accuracy of measuring devices is guaranteed (the largest absolute instrumental fault is $\Delta y = \pm 0.05$ mm);
5. According to the recommendations [42], a reliable probability $\alpha = 95\%$ is set.

It is worth noting that instrumental fault of measuring device is equal to the confidence interval of the values obtained at certain calibration points. Therefore, according to [42-44], we obtain:

$$\Delta_{cal.} = 1 / \sqrt{\sum_{n=1}^n w_n},$$

where:

$$w_n = 1 / \Delta x_n^2,$$

w_n —statistical contribution of the n-th measurement fault;
 Δx_n —n-th measurement fault of the values obtained during calibration.

As a result of the calculations, the calibration error was $\Delta_{cal.} = 0,008$.

The rounded values of the experimental data processing results at each point are written in the form $x = (\bar{x} \pm \Delta x)$.

At the second stage, after processing the experimental values, they were converted into real values according to the calibration chart (Fig. 4) using the indirect measurement processing technique [42, 43].

For this purpose, an equation that approximates calibration chart was found. Considering that each of its points (Fig. 4) has $\pm \Delta a$ dispersion along the ordinate axis, the chart can be approximated by next linear equation [44, 45]:

$$y = a_0 + a_1 x, \tag{1}$$

where equation coefficients [35]:

$$a_1 = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{N \sum x_i^2 - (\sum x_i)^2}, \quad a_0 = \frac{\sum y_i - a_1 \sum x_i}{N}$$

Approximation quality was assessed using the method:

$$e_i = y_i - \hat{y}_i,$$

where:

\hat{y}_i — the function values, calculated using an approximating model.

Sum of squares (SSE) [45]:

$$SSE = \sum_{i=1}^N e_i^2,$$

Determination coefficient R^2 :

$$R^2 = 1 - \frac{SSE}{\sum_{i=1}^N (y_i - \bar{y})^2} \tag{2}$$

where: \bar{y} — the average value of y_i .

The approximation accuracy was $R^2 = 0.9991$, and the equation of the approximated line (Fig. 4.) is as follows:

$$\bar{y}(x) = 0,4587 \cdot x, \tag{3}$$

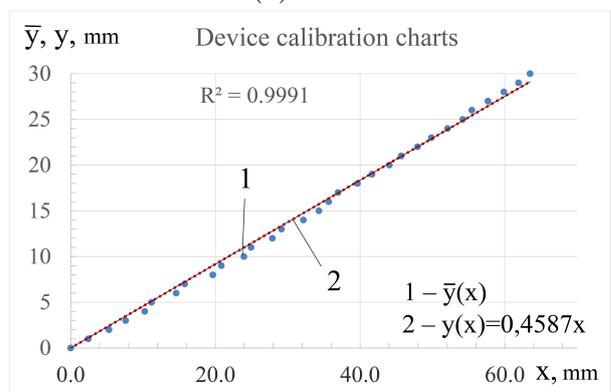


Fig. 4. Device calibration charts: 1 – average value of measurement readings, 2 – approximated line

The values of the actual thread take-up function $P(\varphi)$ and the required thread take-up function $P'(\varphi)$ expressed in real units are:

$$P(\varphi), (P'(\varphi)) = \bar{y}(x(\varphi)) = 0,4587 \cdot x(\varphi) \tag{4}$$

Since the experimental data were processed using the direct measurement method [42, 43], the instrumental error, calculated according to equation (3), is as follows:

$$\Delta y_{in.} = \left| \frac{dy}{dx} \right| \cdot \Delta x, \quad (5)$$

$\Delta y_{in.}$ - instrumental error of the device, mm;

$\frac{dy}{dx}$ - calibration coefficient ($\frac{dy}{dx}=0,4587$);

Δx - instrumental measurement error on the scale ($\Delta x=0,05$ MM), MM.

The analysis of expressions (3) and (5) shows that the instrumental error decreases to $\Delta y_{in.} = 0,023$.

The total error of the results was evaluated taking into account both the instrumental error and the statistical error of the average value. The final error was calculated using the following formula:

$$\Delta_{tot.} = \sqrt{\left(\left| \frac{dy}{dx} \right| \cdot \Delta x \right)^2 + \left(\frac{t_p \cdot S}{\sqrt{N}} \right)^2} + \Delta_{cal.}^2, \quad (6)$$

where: $\Delta_{tot.}$ – total measurement error, mm;

S - standard deviation relative to;

N - number of repeated measurements;

t_p – Student's t-coefficient (for $P=0,95$, $N=10$, $t_p = 2,62$).

The obtained values of actual $P(\varphi)$ and required $P'(\varphi)$ thread take-up functions and faults were rounded to the second decimal place, which is regulated by device accuracy.

In order to determine the correspondence of the value of actual $P(\varphi)$ function to the required $P'(\varphi)$ one, it was determined convergences function $C_i(\varphi)$, as the difference of the values of these functions according to φ argument at the i -th value of technological parameters:

$$C_i(\varphi) = P_1'(\varphi) - P(\varphi) \quad (7)$$

The difference between the values of $P'(\varphi)_{min}$ and $P'(\varphi)_{max}$ functions reflects the total increase of $\Delta(\varphi)$ function due to the change in technological parameters values from the minimum (m_{min} , t_{min}) to the maximum (m_{max} , t_{max}):

$$\Delta(\varphi) = P_2'(\varphi) - P_1'(\varphi), \quad (8)$$

or

$$\Delta(\varphi) = C_1(\varphi) - C_2(\varphi). \quad (9)$$

Estimation of the convergence function $C_i(\varphi)$ allows to detect the difference between actual and required values of thread take-up functions, which values determine stability and quality of the stitch formation process, namely excessive or insufficient thread take-up when sewing materials of different thicknesses and with different stitch parameters, including performing their analysis at limit values.

In order to obtain analytical expressions of thread take-up functions in form of mathematical models, an approximation of the experimental data (x_i, y_i , where $i=1,2,\dots,m_i$) was done using the least squares method.

The analysis of thread take-up functions given in [37] showed that they are piecemeal and their sections are approximated to straight lines or curves of the n -th degree. In order to ensure maximum approximation accuracy for approximation mathematical model, it is advisable to use a

polynomial model of n -th degree [44, 45], determining the type of function and its coefficients depending on the curve (line) nature.

Polynomial model of a piecemeal function of n -th degree:

$$y(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n,$$

where $y(x)$ - the approximate value of the piecemeal continuous function of the thread take-up law ($P(\varphi)$),

x - an independent variable (analogous of the main shaft rotation angle - φ).

The coefficients $a_0, a_1, a_2, \dots, a_n$ were found by minimizing the sum of deviations squares between the experimental values y_i and are calculated by value of the polynomial:

$$S = \sum_{i=1}^m \left(y_i - (a_n x_i^n + a_{n-1} x_i^{n-1} + \dots + a_1 x_i + a_0) \right)^2 \rightarrow \min$$

The partial S derivatives with respect to each coefficient a_k are set to zero, which has the system of equations:

$$\sum_{i=1}^m x_i^k y_i = \sum_{i=1}^m x_i^k (a_n x_i^n + a_{n-1} x_i^{n-1} + \dots + a_1 x_i + a_0),$$

The coefficients $a_0, a_1, a_2, \dots, a_n$ were determined from the system of equations, R^2 determination coefficient is given by (2):

$$\begin{bmatrix} m & \sum x_i & \sum x_i^2 & \dots & \sum x_i^n \\ \sum x_i & \sum x_i^2 & \sum x_i^3 & \dots & \sum x_i^{n+1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sum x_i^n & \sum x_i^{n+1} & \sum x_i^{n+2} & \dots & \sum x_i^{2n} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} \sum y_i \\ \sum x_i y_i \\ \sum x_i^2 y_i \\ \vdots \\ \sum x_i^n y_i \end{bmatrix}.$$

The presented approximation models allow us to determine mathematical thread take-up functions $P(\varphi)$ and $P'(\varphi)$, which can be used for analysis and modeling of stitch type 101 formation process, as well as for optimization synthesis of adaptive thread take-up mechanisms.

III. RESULTS AND THEIR DISCUSSION

Results of experimental studies of thread take-up laws for GK-9-2 sewing machine are given in form of graphic representation of average values of required thread take-up functions $P_1'(\varphi)$ (curve 1, Fig. 5) and $P_2'(\varphi)$ (curve 2), and actual take-up function $P(\varphi)$ (curve 3) (maximum absolute deviation for $P_{1,2}'(\varphi)$ and $P(\varphi)$ function values was $\Delta \bar{y}_n = \pm 0,06$ mm). For an analytical comparison of these functions, Figure 6 presents a diagram of convergence functions $C_i(\varphi)$ values of actual $P(\varphi)$ to required $P_{1,2}'(\varphi)$ thread take-up at maximum and minimum technological parameters. Also on convergence diagram $C_i(\varphi)$ the difference of these functions – $\Delta(\varphi)$, which shows the magnitude and nature of technological parameters impact on the required function of the actual thread take-up $P'(\varphi)$ is shown. Approximation results (Table 2, Fig. 7) of experimental data, represented by mathematical models of piecemeal-continuous dependencies of thread take-up at different technological parameters of chain stitch on GK-9-2 machine, are given in table 1.

Analysis of actual $P(\varphi)$ and required $P_1'(\varphi)$ and $P_2'(\varphi)$ thread take-up functions (curve 3 and curves 1, 2 Fig. 5) showed that required thread take-up $P_1'(\varphi)$ significantly differs from actual $P(\varphi)$, and in different moments of the stitch formation process, these values are different. Also analysis of diagrams of thread take-up functions $P(\varphi)$ and $P'(\varphi)$ showed that in range φ_{0-3} , thread take-up process takes

place, required for passing the thread loop through the materials and forming the previous thread loop. At the same time, the amount of supplied thread is excessive (maximum value of the convergence function is $-C_{1,2}(\varphi_{0-3}) \approx 18 \div 30$ mm), which leads to thread sagging. In the range φ_{3-4} accordingly to requirements for required thread take-up function $P'(\varphi)$ specified in works [36, 37], shortening of previous thread loop which is coming out from the expander's nozzle after it was "stabbed" by needle is necessary (Fig. 1, b). However, in real stitch formation process this is impossible to achieve. Firstly, in φ_{0-3} range of stitch formation process an excess of supplied thread is created by thread take-upper ($C_{1,2}(\varphi_{0-3}) \approx 30 \div 18$ mm). Secondly, it is possible to shorten loop of the needle thread only to dimensions limited by needle shaft (Fig. 1, b). And finally, taking into account that total surfaces coverage angle by the thread from the approaching branch of the loop BC (Fig. 1, b) to NC circuit section is about $3,5\pi$, this is practically impossible to do. Therefore, the selection of excess thread begins in φ_{7-8} period respectively at the moments determined by intersections of functions $P_{1,2}'(\varphi)$ and $P(\varphi)$ charts respectively at points A and B (Fig. 5, 6).

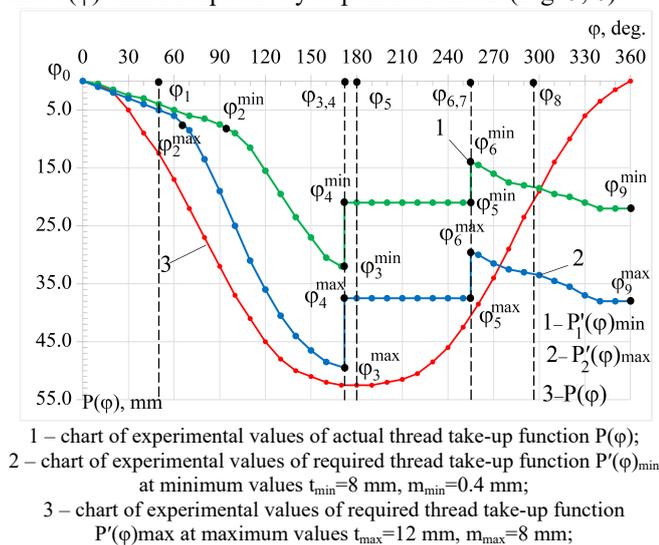
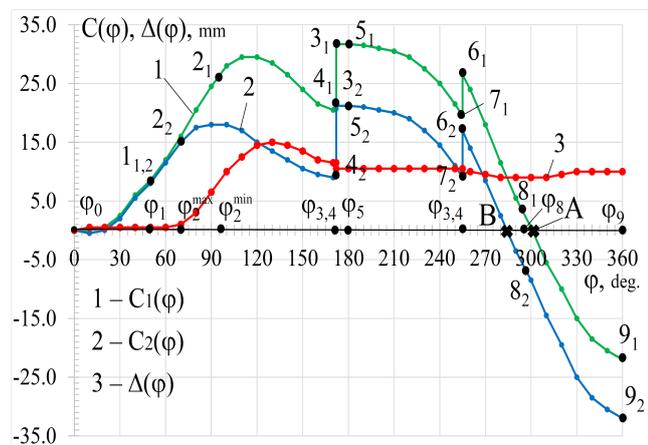


Fig. 5. Thread take-up charts for GK-9-2 sewing machine



1 – chart of correspondence functions $C_1(\varphi)$ at minimum parameters t_{min} and m_{min} ; 2 – chart of correspondence functions $C_2(\varphi)$ at maximum parameters t_{max} and m_{max} ; 3 – chart of increase $\Delta(\varphi)$ of function of required thread take-up when changing technological parameters from minimum to maximum

Fig. 6. Diagram of convergence $C_i(\varphi)$ and growth functions of the required thread take-up $\Delta(\varphi)$ of GK-9-2 sewing machine at minimum $i=1$ and maximum $i=2$ technological parameters

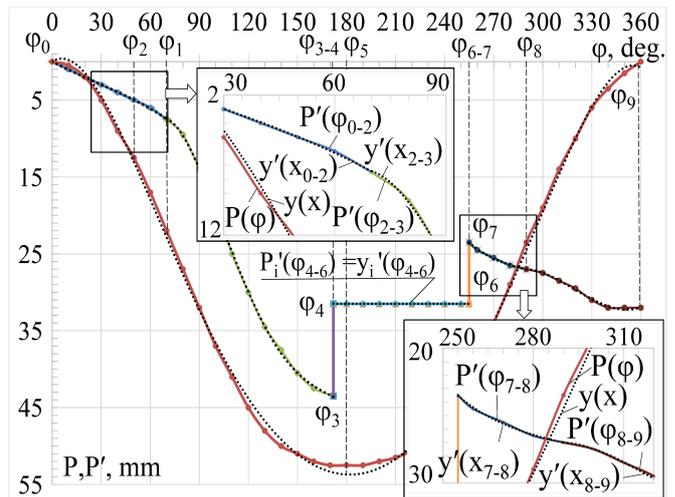


Fig. 7. Graphical representation of mathematical models of $P(\varphi)$ and $P'(\varphi)$ thread take-up functions in general view

At the same time, in the works [24] it is noticed that reduction of the needle thread loop for stitch type 401 occurs in 2 stages, partly in the same period φ_{0-4} when moving needle to the lowest position and tightening the stitch in period φ_{8-9} . Which indicates the uniqueness of formation processes for this stitch type and distribution of load on the thread throughout stitch formation process. In period φ_{4-6} , "overflow loop" formation occurs and it's captured by expander's nozzle, in period φ_{6-7} , the excess "overflow loop" is reduced to the size of expander, these processes also cannot be provided with actual thread take-up function $P(\varphi)$, since thread take-up process occurs with an excess of supplied thread ($C_{1,2}(\varphi_{6-7}) \approx 21 \div 9$ mm). In period φ_{7-8} , thread loop is expanded by the expander, which starting from the moment φ_8 happens simultaneously with materials movement up to the moment φ_1 , these processes can be performed up to the moments φ_A and φ_B . Depending on technological parameters values stitch tension and winding thread from the bobbin occurs in periods φ_{A-9} and φ_{B-9} . The first thing to note is that period φ_{A-B} arises as result of technological parameters changes (stitch length t and material thickness m) and it is an indicator for moments when stitch tightening process begins. The duration of this period shows how these parameters affect machine cycle, determining the time available for thread tightening and winding, which in its turn affects stitch quality.

It should be noted that for different technological materials t and m convergence functions $C_1(\varphi)$ and $C_2(\varphi)$ (Fig. 6) have different values, due to the fact that GK-9-2 machine does not provide ability to adjust actual thread take-up value $P(\varphi)$, and its value satisfies the conditions only with maximum parameters values, that is confirmed by smaller function values in comparison with minimum technological parameters ($C_2(\varphi) < C_1(\varphi)$). Analysis of the diagram in Fig. 6 shows that at minimum parameters value of actual thread take-up $P(\varphi)$ exceeds the required one by 64.1%, indicating excessive take-up, while at maximum parameter values the mismatch function $C_2(\varphi)$ exceeds the required one by only 20.7%.

The increase $\Delta(\varphi)$ (curve 3, Fig. 6) of required thread take-up function $P'(\varphi)$ due to changes in technological parameters is approximately linear, which is associated with an increase in size of thread loop, which is passed into material by needle, due to increase in material thickness.

Table II
Mathematical models of thread take-up functions

Mar- king	Interval range	Coefficients of mathematical models of thread take-up functions				
		P ₁ (φ)	P ₂ (φ)	Δ(φ)	P(φ)	
φ ₀₋₁		$y'_i(x_{0-2}) = a_{i3}x^3 + a_{i2}x^2 + a_{i1}x + a_{i0}$				
φ ₁₋₂ (x ₁₋₂)	0-95°(68°)	a ₁₀ =0; a ₁₁ =-0,0629; a ₁₂ =-0,0006; a ₁₃ =4·10 ⁻⁶ ; R ² = 0,9971	a ₂₀ =0; a ₂₁ =-0,111; a ₂₂ =0,006; a ₂₃ =-8·10 ⁻⁶ ; R ² = 0,9971	a ₃₁ =-0,1053; a ₃₂ =0,0077; a ₃₃ =-0,0003; a ₃₄ =4·10 ⁻⁴ ; a ₃₅ =-2·10 ⁻⁸ ; R ² = 0,9994	$y(x) = a_6x^6 + a_5x^5 + a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0$ a ₀ =0; a ₁ =0,1373; a ₂ =-0,0126; a ₃ =0,0001; a ₄ =-5·10 ⁻⁷ ; a ₅ =1·10 ⁻⁹ ; a ₆ =-1·10 ⁻¹² ; R ² =0,9986	
φ ₂₋₃ (x ₂₋₃)	95(68)- 172°	a ₁₀ =-113,73; a ₁₁ =2,9083; a ₁₂ =-0,0242; a ₁₃ =5·10 ⁻⁵ ; a ₁₄ =3·10 ⁻⁸ ; R ² = 0,9997	a ₂₀ =-167,64; a ₂₁ =6,211; a ₂₂ =-0,0819; a ₂₃ =0,0004; a ₂₄ =-8·10 ⁻⁷ ; R ² = 0,9997	a ₃₀ =-493,9; a ₃₁ =24,662; a ₃₂ =-0,492; a ₃₃ =0,0051; a ₃₄ =-3·10 ⁻⁵ ; a ₃₅ =9·10 ⁻⁸ ; a ₃₆ =-1·10 ⁻¹⁰ ; R ² = 0,9997		
φ ₄₋₆ (x ₄₋₆)	172-255°	y ₁ =-21 R ² = 1	y ₂ =-31,5 R ² = 1	y ₃ =-10,5 R ² = 1		
φ ₇₋₈ (x ₇₋₈)	255-288°	$y'_i(x_{7-8}) = a_{i3}x^3 + a_{i2}x^2 + a_{i1}x + a_{i0}$				
φ ₈₋₉ (x ₈₋₉)	288-360°	a ₁₀ =568180; a ₁₁ =-8637,6; a ₁₂ =52,46; a ₁₃ =-0,1591; a ₁₄ =2·10 ⁻⁴ ; a ₁₅ =-1·10 ⁻⁷ ; R ² = 0,9998	a ₂₀ =150587; a ₂₁ =-2347,1; a ₂₂ =14,597; a ₂₃ =-0,0453; a ₂₄ =7·10 ⁻⁵ ; a ₂₅ =-4·10 ⁻⁸ ; R ² = 0,9982	a ₃₀ =54276; a ₃₁ =-1009,4; a ₃₂ =7,7736; a ₃₃ =0,0051; a ₃₄ =7·10 ⁻⁵ ; a ₃₅ =-9·10 ⁻⁸ ; a ₃₆ =4·10 ⁻¹¹ ; R ² = 0,9927		

However, the nature of these changes could be more complex, requiring more in-depth research.

The negative values of curves 1 and 2 (Fig. 6) illustrate beginning of stitch tightening process at points "A" and "B". The analysis shows that at maximum values of stitch size and material thickness (curve 2) tightening occurs earlier, before the start materials movement (φ₈), while at the minimum parameters tightening occurs simultaneously with materials movement. This indicates that stitch tightening conditions depend on technological parameters, and these point require further research. Also it can be concluded that with different technological parameters, stitch quality changes, since the law of actual thread take-up P(φ) remains unchanged.

The adjustment of the actual thread take-up P(φ) in machines of this design series is mostly done by changing force on stitch regulator, that can cause thread take-up instability. This phenomenon depends on such parameters as thread thickness, elasticity and coefficient of thread friction with other mechanism elements. Deviations can be caused by dynamic processes in thread take-up circuit, its elastic deformations or design features of machine.

The obtained mathematical models of thread take-up function (Table 2, Fig. 7) can be used for analytical description of take-up laws during the design of thread take-up mechanisms and maintenance this type of equipment. They serve as basis for further, deeper research aimed to

improve obtained mathematical models for required and actual thread take-up, taking into account its physical and mechanical properties, such as stiffness, deformability and friction. This allows to expand analytical capabilities and consider more precisely kinematic and dynamic characteristics when studying thread take-up process.

Additionally, these models can be used in development of thread take-up mechanisms with possibility of automated regulation of thread take-up law when performing such operations, where change in technological parameters values occurs during sewing process. This, in turn, ensures adaptation of thread take-up mechanisms to different operating modes of sewing machine, minimizes process instability and improves quality of stitch formation.

IV. CONCLUSIONS DISCUSSION

1. Excessive thread take-up, conditioned by design features of take-up mechanisms is observed in single-thread chain stitch sewing machines of type 101. This can lead to excess of required take-up by 20–64%, that relates to discrepancy between actual and required thread take-up. The deviations are caused by design limitations of the take-up mechanism or impact of physical and mechanical thread properties.

2. The lack of thread take-up adjustment leads to its variability depending on technological conditions, which is

compensated by redistribution of thread from previous stitches and changing the force on stitch regulator. This reduces thread take-up stability and limits its adaptation to different material thicknesses and stitch lengths.

3. It has been established that at maximum values of technological parameters the process of stitch tightening begins earlier than at minimum values, when it matches with material movement. To achieve stable quality of materials stitching it is necessary to consider that initial moments of stitch tightening depend on specific conditions, such as stitch length and material thickness. To ensure process stability it is necessary to adapt thread take-up function to the required conditions, which will allow to reduce $\phi A - \phi B$ interval to zero, providing the same conditions for stitch tightening.

4. The application of the obtained mathematical model of thread take-up process allows to consider its dynamic and physico-mechanical characteristics under different conditions and technological parameters, when analyzing thread taking-up process, that simplifies calculations related to analysis of thread taking-up and synthesis of new mechanisms. They can also be used to develop mechanical systems for auto adjustment of thread take-up value when changing technological parameters during sewing process, that will allow to achieve greater compliance of thread take-up functions values, and, therefore, improve products quality.

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