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ASSESSING THE IMPACT OF SEWING MACHINE THREAD TAKE-UP MECHANISM PARAMETERS ON THE MAGNITUDE AND NATURE OF THREAD TAKE-UP

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The subject of this study is the needle thread take-up mechanisms (NTTM) of modern chain stitch sewing machines of classes 400 and 600. The principal issue with these mechanisms is the complexity of their adjustment because of the large number of adjustable parameters and the need for clear recommendations for proper setup, which negatively affects their performance.

The research involved analyzing the impact of NTTM's kinematic parameters and various thread path configurations in machines. The study revealed new patterns that allow for more precise thread take-up regulation, enabling better synchronization of the actual thread take-up with the required amount, thereby improving stitch quality and increasing sewing process productivity. Accurate thread take-up adjustment prevents excessive or insufficient thread tension, a common issue when sewing materials with variable thickness or stitch length.

The results can be used to adjust sewing machines and automate the tuning of technological processes by changing the adjustment parameters with variations in technological parameters. This is particularly important in producing 3D textile structures for reinforcing composite molds, where adjusting for average material thickness can cause thread tension issues when the current thickness changes. The practical application of these results will ensure stable sewing quality based on stitch parameters, which is relevant for automating machine settings and working with materials of varying thicknesses. The proposed recommendations will improve the manufacturing process and increase equipment efficiency

Keywords: sewing machine, chain stitch, thread take-up, thread take-up function, adjustment parameters

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1. Introduction

Sewing technologies are widely used for processing various materials, manufacturing clothes and other products for various purposes. Chain stitch sewing machines, due to their advantages over shuttle machines and the constant expansion of the range of materials, are increasingly used in the sewing industry. These types of machines are produced worldwide by dozens of companies such as Juki, Yamato, Pegasus, Bruce, Siruba, Kansai-Special, and others. The number of classes of machines and their modifications is measured in the hundreds and is constantly growing.

At the same time, technological processes, that is, the types of stitches performed on this equipment, are updated very infrequently. According to ISO 4915:1991, there are only 49 types of chain stitches and, accordingly, the methods of their formation (of them single-threaded – 7, multi-threaded – 26, edging – 16). Another dozen or two of these techniques can be found in patent materials, and the application of the procedure from [1] makes it possible to generate dozens more new types of stitches with different properties. Even fewer of these methods are implemented in industrial equipment, certain types of class 100 stitches are used, in particular, for the manufacture of 2D, 3D frame textile products [2, 3] for the creation of pre-forms in mechanical engineering from composite and hybrid materials based on fibers [4], as well as other materials. This is primarily due to the simplicity of the processes of their formation, high elasticity. Instead, the use of single-thread chain stitches, which are characterized by self-dissolving, reduces the quality of the finished product, or complicates the processes of further processing. The use of multithread chain stitches is limited by the conditions of their formation. The quality of the stitch is of great importance and depends on numerous parameters. Firstly, on the coordination of the working bodies, the conditions for performing characteristic operations (capturing the "loop-loop", "stabbing" thread triangles, the beginning of transporting materials and tightening the stitch, the moment of dropping the loops of needle threads, etc. Second, the high-quality performance of these moments directly is provided by the value of the maximum coincidence of the values of the actual $P(\varphi)$ and the required $P'(\varphi)$ needle and looper threads [5]. It is important to note that the technological parameters of the stitch (type, material thickness, length, and type of threads) have a direct effect on the law of the required thread take-up $P'(\varphi)$. On the other hand, the parameters of NTTM thread take-ups and thread guides determine the nature and value of the actual thread take-up $P(\varphi)$ [5], which is more precisely adjusted by changing the adjustable parameters of NTTM. In the operating instructions, the quantitative influence of these parameters is not specified, and they are established by trial and error, which significantly affects the time of setting up machines and the quality of stitches.

Thus, research in this area is relevant due to the expansion of the application of sewing technologies. This emphasizes the need for flexible systems for automated regulation of thread take-up in sewing machines and the possibility of implementing technological processes, especially when working with materials of variable thickness and new types of stitches.

2. Literature review and problem statement

Sewing technologies are widely used for various operations, however, the issue of maintaining the quality of the stitch when changing technological parameters and the process of its formation is only partially solved in work [5] by setting adjustable parameters. This is especially noticeable when connecting parts with a significant difference in thickness, which is an important aspect in the production of pre-forms based on sewing technologies [2, 3]. However, the issue of optimization of these technologies remains insufficiently researched. The analysis of the mentioned sources shows that the issues of the stability of thread connections under the conditions of sharp changes in thickness and ensuring uniform thread tension during their formation remain unresolved.

In work [6], the issue of reinforcing pre-forms based on 2D textiles was solved with the help of embroidery machines with a class 101 stitch. However, this process is not suitable for stitching packages with different thicknesses due to the structure of the stitch and its limitation at significant differences in thickness without changing its structure. At the same time, the evaluation of chain stitch type 401 reinforcement in work [7] shows that this type of stitch is more effective, but its structure when stitching materials with different thicknesses was not investigated.

Methods for reinforcing carbon materials of different thicknesses are considered in works [8, 9] and wrinkle defects that arise due to uneven tension of the stitches during stitching of materials with different thicknesses are described. However, the problem of adjusting the amount of tension or thread take-up is not considered. Along with this, there are methods of automatic control of thread tension in the process of forming shuttle stitches [10], which partially solve the problem of stitching materials of variable thickness within ±3 mm. In addition, the proposed methods for predicting wrinkle defects by modeling [11] do not eliminate the problem of displacement of layers, which occurs as a result of reinforcement with thread stitches.

Studies on the structure of the type 406 stitch [12, 13] showed that both the type of materials and the number of its layers (thickness of the materials) affect the total amount of the supplied thread. The proposed geometric models and analytical expressions make it possible to determine only the total amount of thread that is used for one stitch and make it possible to determine only the technological parameters of the stitch. Similar research methods were applied for stitch types of class 300, 401 [14], and 500 [15]. It should be noted that in works [13, 14] the sources of the used information should be arranged in order, regression models are proposed, which also take into account the tension of each thread. This can be useful for quality control over the technological parameters of the stitch and determining the required thread tension.

However, these works do not contain specific recommendations for adjusting the thread tension force in the feed mechanisms of sewing machines and do not solve the problem of correspondence between the actual $P(\varphi)$ and the required $P'(\varphi)$ thread take-up. This is also complicated by the fact that thread take-up mechanisms [16, 17] have various designs and adjustable parameters, which indicates that the issue of thread take-up is mainly solved by structural methods.

Studies on the process of forming a stitch of type 406 [5] showed that the required thread take-up $P'(\varphi)$ depends on the movement of working bodies and technological parameters of the stitch. These factors can lead to sharp changes in the values of $P'(\varphi)$, which requires correction of the actual thread take-up $P(\varphi)$. This must be taken into account when stitching materials with large differences in thickness, for example, when manufacturing 3D frame textile materials for pre-forms by the proposed methods [8, 9].

Work [5] also notes that the maximum value of $P'(\varphi)$ is directly proportional to the length of the stitch and the thickness of the material. The discrepancy between the actual feed and the required one is partially compensated by the elastic properties of the thread and the adjustment of the parameters of the feed circuit. However, studies show that this compensation is insufficient, and excessive thread take-up leads to weak connections, while adjusting the amount of thread take-up using nomograms [5] does not make it possible to change the nature of thread take-up.

The optimal solution to the problem is achieved only thanks to the precise adjustment of the kinematic parameters of the thread take-up mechanisms. However, the quantitative characteristics of the influence of these parameters on the actual delivery function have not been investigated.

The relevance of designing thread take-up mechanisms of technological machines is considered in works [18–20]. The proposed technique makes it possible to determine their optimal parameters due to the design of not only the thread take-up contour [19], but also the influence of the parameters of the guide surfaces [20]. However, in the calculations, the projection of the spatial contour of the thread take-up on the plane was accepted, and the accuracy of the accepted assumptions was not evaluated. Similar assumptions were accepted in works [5, 18], in which the influence of the location of the thread guides along the Z axis was not taken into account during the studies of the thread take-up function, which casts doubt on the results. To verify these assumptions, it is necessary to compare the influence of the spatial and plane coordinate systems on the function of the actual thread take-up $P(\varphi)$, taking into account the location of thread guides and thread take-ups, which is an urgent task.

Our review of the literature reveals the need to study the technological processes of sewing production, taking into account the variable parameters of thread take-up mechanisms. The identified regularities will make it possible to devise recommendations for setting up equipment for technological processes with significant differences in the thickness of materials, which will ensure stability and high quality of stitch formation, in particular, in the production of pre-forms based on sewing technologies.

3. The aim and objectives of the study

The purpose of our research is to determine the patterns of actual thread take-up in the mechanisms of modern chain stitch sewing machines under various technological conditions, which will reduce the time spent on their adjustment and increase their efficiency.

To achieve the goal, the following tasks were set:

– to determine the influence of kinematic parameters on the function of actual thread take-up $P(\varphi)$, establish the adjustment range, and provide appropriate recommendations for modern chain stitch sewing machines;

– to analyze the basic Thread take-up contours in sewing machines in order to identify the nature of their influence on the function of the actual thread take-up $P(\varphi)$;

– to assess the need to take into account the spatial arrangement of the elements of the thread take-up mechanisms during their study.

4. The study materials and methods

4. 1. The object and hypothesis of the study

This paper examines the thread take-up mechanism of the Juki MF-7923D sewing machine (Japan). The object of research is the kinematic parameters of this mechanism, including their variations and limit values that affect the quality of stitch formation.

The main hypothesis assumes that the change in the laws of movement of thread take-ups due to the kinematic parameters of the thread take-up mechanism and Thread take-up contours directly affects the function of the actual thread take-up $P(\varphi)$. This makes it possible to find ways of better matching between the actual $P(\varphi)$ and the required $P'(\varphi)$ take-up. At the same time, it is necessary to evaluate the expediency of taking into account the spatial coordinate system during calculations.

The parameters of the thread take-up mechanism in the MF-7923D sewing machine are considered, including possible variations of these parameters and their limit values, which serve to calculate the functions of the position of the working bodies of the thread take-up mechanism and the function of the actual thread take-up. To this end, the mathematical apparatus of vector algebra and the method of vector transformation of coordinates are used, which applied for kinematic analysis of spatial mechanisms with structural groups of the second class. The analytical approach makes it possible to determine the functions of the actual thread take-up as the instantaneous sum of the sections of the feed contour, taking into account the change in the parameters of the mechanism.

4. 2. Description of the research object and parameters

Fig. 1 shows the general scheme of taking up the thread in the MF-7923D Juki sewing machine [21]. The take-up circuit $G_{0.1,2,3}$ – $N_{1,2,3}$ (Fig. 1) for needle threads includes a system of thread guides $G_{i.j}$, thread take-ups $T_{i.j}$ and needle eyes N_j, where the ith number corresponds to the serial number of the thread guide (thread take-up) for the jth needle. The first needle (j=1) corresponds to the one in which the nose of the looper first captures its "loop of the opening".

The thread take-up circuit begins with the thread guides $G_{0.1,2,3}$ (Fig. 1), after the thread tension regulator, and ends with the eye of needles $N_{1.1,2,3}$ at its uppermost position (UP). Thread guides $G_{3.1}$, $G_{3.2}$, $G_{3.3}$ are adjustable along the Y axis for each needle. In addition, this circuit includes a rocker thread take-up $T_1(\varphi)$ with holes $T_{1.j}$, the U-shaped thread guide of the surface of which forms a 3D contact at points $G_{4.j}$–$G_{5.j}$. The thread take-up $T_2(\varphi)$ with the corresponding holes $T_{2.j}$ are fixed on the needle guide, the fixed $G_{6.j}$ and the movable $G_{8.j}$ thread guides, respectively, are fixed on the machine body and made in the needle holder of the needles. In addition to the main thread tension regulator, the $G_{7.j}$ thread guide (Fig. 1, 2, *a*, *b*) is used in NTTM of the MF-7923D Juki machine, which is made in the form of an additional threader $G_{7.j}$. At the same time, depending on the type of feed circuit, it is fixed on the body of the machine $G_{7.j}$ (Fig. 2, *a*) or on the needle holder $T_{3.j}(\varphi)$ ($G_{7.j}$) (Fig. 2, *b*) [21].

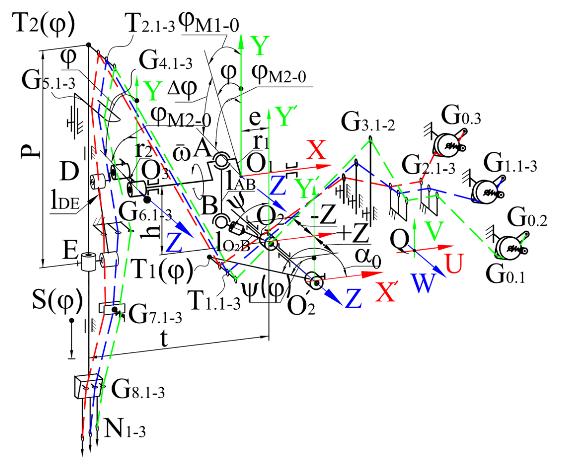
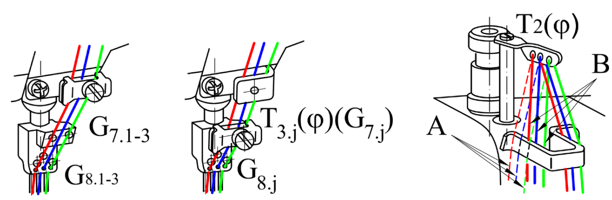


Fig. 1. Calculation diagram of the needle thread take-up mechanism in the MF-7923D Juki sewing machine



a *b* *c*

Fig. 2. Thread take-up scheme [21]: *a* – position of additional thread clamp $G_{7.j}$ for elastic thread; *b* – position of additional thread clamp $T_{3.j}$ ($G_{7.j}$) for low-stretch thread; *c* – position of the thread on the U-shaped thread guide $G_{4.j}$–$G_{5.j}$ for highly elastic thread (dash-dotted line A) and low-stretch thread (solid line B)

The law and magnitude of the movements of thread take-ups $T_1(\varphi)$ and $T_2(\varphi)$ depend on the parameters of the links of the kinematic chains, respectively O_1ABO_2 and O_3DE (Fig. 1). The parameters of these kinematic chains for the MF-7923D Juki machine are given in Table 1. The nature of the influence of adjustable parameters α_0, R on the function $P(\varphi)$ was studied in [5] using the example of similar NTTMs in machines W562-05BB Pegasus [22] and CF 2300M-164M Uamato [23].

Table 1

NTTM kinematic parameters

O_1A (r_1)	AB (l_{AB})	O_2B (l_{O_2B})	z	t	e	h	O_3D (r_2)	DE (l_{DE})	P	R	α_0	ψ
mm											degree	
4	32	21.5	0	120	21	32	15.5	54.5	127	85	158.6	169.3

Structurally, the structure of the kinematic chain of the thread take-up T_{1j} and similar NTTM models [5] provides for the possibility of adjusting its parameters R and α_0 (Fig. 4, *a*), the amount of stroke ψ_x and the law of motion of the thread take-up $T_1(\varphi)$ (Fig. 3, *b, c*). The mutual phase position $\Delta\varphi$ (Fig. 1) of the cranks O_3D and O_1A, according to the mechanism of the needle and thread take-up T_{1j} [21] is set by the parameter $\pm\Delta\varphi$. These adjustments depend on the geometric parameters of the kinematic chain O_1ABO_2 of the thread take-up T_{1j} and are set by adjusting the eccentricity value r_1 (Fig. 1) of the eccentric O_1A and its phase position $\Delta\varphi$ on the main shaft by installing it on the shaft (Fig. 3, *b*). In addition, a more precise setting of NTTM is performed by changing the position of rocker arm 1 – (O_2B) (Fig. 3, *c*) on shaft 2 of thread take-up T_{1j} and is set by the $\pm z$ parameter (Fig. 1).

The T_{2j} thread take-up, in turn, is fixed at the end of the needle guide and has a common kinematic chain with the O_3DE needle mechanism (Fig. 1). In the machines of the MF-7900 Juki model series, adjustment of the needle stroke is provided due to the execution of the eccentric spike of the O_3D crank (r_2) in the range of the needle stroke S_x=31÷33 mm (r_2=15.5÷16.5 mm).

In the NTTM of the MF-7923D Juki machine, all thread guides G_{ij} and thread take-ups T_{ij} have the corresponding coordinates (Fig. 1).

At the same time, for the convenience of calculating and adjusting the parameters in practice, we shall introduce the concept of the global – XYZ – and local – UVW – coordinate systems of NTTM (Fig. 3, *c*). The origin of the global XYZ coordinate system is placed in the O_1A crank rack, i.e., O_1 (Fig. 1). In turn, the origin (point Q (9.5; 23.5; 0)) of the local UVW coordinate system corresponds to the reference point of adjustments of the MF-7923D Juki machine.

The feed contour is selected according to recommendations form [21]: for highly elastic threads – type "A" (Fig. 2, *a, c*), for others – type "B" (Fig. 2, *b, c*).

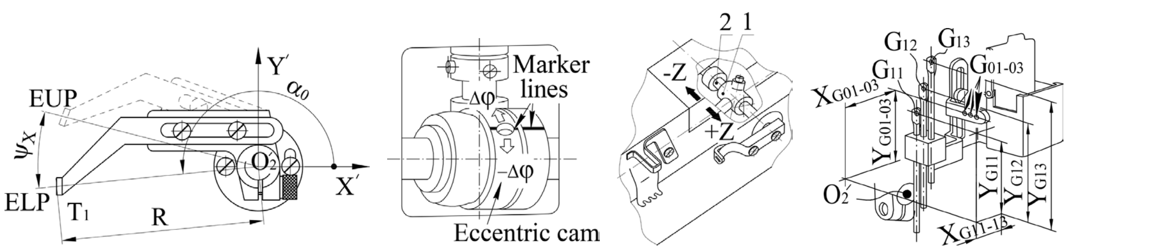
The coordinates of the elements $G_{i,j}$, T_{1j}, T_{2j}, N_j of both feed circuits "A" and "B" of the MF-7923D Juki machine, according to the instructions [21] on adjustments, are listed in Table 2.

The parameters given in Table 1 will be used to determine the position functions of thread take-ups $T_{ij}(\varphi)$. Accordingly, the values of parameters from Table 2 served to identify the regularities of the influence of the feeding contours "A" and "B", which is necessary to evaluate the efficiency of the thread take-up mechanism in the Juki MF-7923D sewing machine.

4. 3. Description and characteristics of the actual thread take-up contours

In NTTM with a branched kinematic chain and a fixed thread guide of the U- or I-type [5], thread take-up circuits of the "A" or "B" type are provided (Fig. 4, *a, b*). Accordingly, they contain a certain number (n) of variable elementary sections $p_{i-1.j-i.j}(\varphi)$ and sections $p_{i-1.j-i.j}$ of constant length $l_{i,j}(\varphi)l_{i,j}(\varphi)$. The number of elementary sections in the periods of a stitch formation process changes by dividing the division of elementary sections $p_{T1.j-T2.j(\varphi)}$ (Fig. 4, *a, b*) into sections $p_{T1.jG4.j(\varphi)}$ and $p_{G4.j-T2.j}(\varphi)$ at point $G_{4.j}$.

With the feed circuit of type "A" (Fig. 4, *a*), the thread contacts the surfaces of the U-shaped thread guide (Fig. 2, *c*), and the thread clamp G_{7j} is fixed on the machine body (Fig. 2, *a*). When using low-elastic threads, the feed circuit "B" is used, where the threads can interact with only one surface of the U-shaped thread guide. In this way, an I-shaped thread guide [5] with a 3D contact at points G_{4j} is artificially created (Fig. 4, *b*).



a *b* *c* *d*

Fig. 3. Adjustment parameters of the thread take-up $T_{1.j}$ and the start of the local coordinate system UVW [23]: *a* — parameters α_0 and R; *b* — adjustment of the eccentricity value (r_1) of eccentric O_1A; *c* — parameter of the position of the rocker O_2B relative to the axis ($\pm z$); *d* — origin of the local UVW coordinate system (for the MF-7923D Juki machine, point Q(30; 35; 0) relative to O_2)

Table 2

Coordinates of thread guides and thread take-ups in the local UVW coordinate system

$G_{i,j}$			0	1	2	3	4	5	6	7 A	7 B	8	T_{1j}	T_{2j}	N_j
			i										UP*		
1	*j*	*u*	102	32	−8	−29	−145	−155	−146	−146	−146	−146	−150	−109*	−154
		v	−45	8.5	8.5	0	55	55	−22	−95	−167	−177	85*	−4*	−210*
		w	52	68	68	62	50	50	35	22	8	3	40*	50	0
2		*u*	87	32	−8	−29	−145	−155	−150	−150	−150	−150	−150	−109*	−150
		v	−11	8.5	8.5	12	55	55	−22	−95	−167	−177	85*	−4*	−207*
		w	60	65	−65	58	44	44	35	22	8	3	35	44	0
3		*u*	70	32	8	−29	−145	−155	−154	−154	−154	−154	−150	−109*	−146
		v	22	8.5	8.5	24	55	90	−22	−95	−167	−177	85*	−4*	−203*
		w	67	62	62	54	40	40	35	22	8	3	32	40	0

*Note: * – the coordinates are indicated at UPs of thread take-ups T_1 and T_2.*

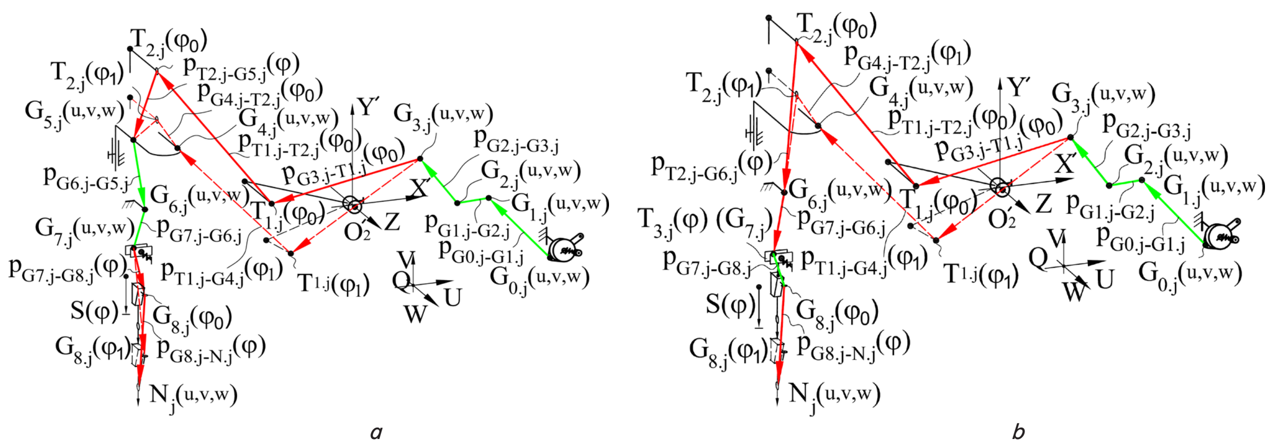


Fig. 4. Thread take-up contours according to thread type:
a – "A" type for highly elastic threads; *b* – "B" type for low-elastic threads

For the take-up circuit "B" (Fig. 4, *b*), the thread clamp $G_{7.j}$ performs the functions of the needle feeder $T_3(\varphi)$, which is fixed on the needle guide (Fig. 2, 4, *b*), with the law of motion $S(\varphi)=T_2(\varphi)=T_3(\varphi)$. The influence of the thread take-up $T_3(\varphi)$ on the law of actual thread take-up $P(\varphi)$ is ambiguous, as it creates additional tension of the thread in the area of "stitches" – $T_3(\varphi)$ and $G_{0.j\text{-}T3(\varphi)}$. Depending on the condition of tension force equilibrium in the sections $p_{G6.j\text{-}T3.j}(\varphi)$ and $T_{3.j}(\varphi)-G_{8.j}(\varphi)$ (Fig. 3, *b*), the thread clamp $G_{7.j}$ can act as a thread take-up $T_{3.j}(\varphi)$, and as thread guide $G_{7.j}$. Since its influence can be investigated only when calculating the function of take-up of real threads, it was assumed that the thread does not move relative to the thread clamp $T_{3.j}(\varphi)$.

Contact condition of thread guide G_4 with elementary section $p_{T1.j\text{-}T2.j}(\varphi)$:

$$p_{T1.j-G4.j-T2.j}(\varphi)= \left\| \begin{array}{l} \left(p_{T1.j-G4.j.}(\varphi)+p_{G4.j-T2.j}(\varphi)\right) \text{if } \varphi_{1-3}\geq\varphi\geq\varphi_{2-3}, \\ p_{G1.j-T2.j}(\varphi) \quad \text{otherwise}, \end{array}\right. \quad (1)$$

where $\varphi_{1\text{-}3}$, $\varphi_{2\text{-}3}$ are the phase angles of rotation of the main shaft at which the thread contacts the guide G_4.

4. 4. Determining the functions of actual thread take-up

When modeling the thread take-up process, it is assumed that the thread is ideal: inextensible, absolutely flexible, and the frictional forces obey Amonton's law [24].

This simplification makes it possible to obtain preliminary calculation results with reasonable accuracy [5]. In addition, it makes it possible to carry out a comparative analysis of the laws of feeding an ideal thread under different conditions of stitch formation, using different contours of needle take-up and values of kinematic parameters of the mechanism.

To determine the function of actual take-up of the ideal thread $P(\varphi)$ for each needle, expressions are applied according to the calculation schemes (Fig. 3, *a*, *b*). Thus, the function of actual thread take-up $P(\varphi)_j^k$ for each needle will be piecewise continuous for all types of thread take-up contours and is determined according to the methodology from [5]:

$$P(\varphi)_j^k=\xi^k_{(0.j)}-\xi^k_j(\varphi), \quad (2)$$

$$\xi^k_{0.j}=\xi_{i=1\,j=1}^{i=n,j=m} p^0_{i.j},\ \xi^k_j(\varphi)=\sum\nolimits_{i=1\,j=1}^{i=n,j=m} p_{i.j.}(\varphi),$$

where $\xi^k_{0.j}$, $\xi^k_j(\varphi)$ is the length of the *k*-th type of "feed circuit" (type "A", type "B") for a specific *j*-th needle, respectively, at the value of the argument $\varphi=0°$ and the current value of the rotation of the main shaft of the machine φ mm; $p^0_{i.j}$, $p_{i.j}(\varphi)$ is the length of the *i*-th section of the *k*-th type of "feed circuit" (type "A", type "B") for a specific *j*-th needle, respectively, at the value of the argument $\varphi=0°$ and the current value of rotation of the main shaft of the machine φ.

The contour of the thread depending on the type of "feed contour" k=A and k=B (Fig. 4, *a*, *b*) and under the condition of the contact of the elementary section $p_{T1.j\text{-}T2.j}(\varphi)$ (1), represented as a sum of free vectors , built between the corresponding thread guides $G_{0.j}$, $G_{1.j}$, $G_{3.j}$, $G_{4.j}$, $G_{5.j}$, $G_{6.j}$, $G_{7.j}$, $G_{8.j}$, N_j and thread take-ups $T_1(\varphi)$, $T_{2.j}(\varphi)$, $T_{3.j}(\varphi)$.

The length of the common section of both contours $\xi_{1.j}(\varphi)$:

$$\xi_{1.j}(\varphi)=p_{G0.j-G1.j}+p_{G1.j-G2.j}+ +p_{G2.j-G3.j}+p_{G3.j-T1.j}(\varphi).$$

Under condition $G_4\notin p_{T1.j\text{-}T2.j}(\varphi)$:

$$\xi^A_j(\varphi)=\xi_{1.j}(\varphi)+p_{T1.j-T2.j}(\varphi)+ +p_{T2.j-G5.j}(\varphi)+p_{G5.j-G6.j}+p_{G6.j-G7.j}+ +p_{G7.j-G8.j}(\varphi)+p_{G8.j-N.j}(\varphi), \quad (3)$$

$$\xi^B_j(\varphi)=\xi_{1.j}(\varphi)+p_{T1.j-T2.j}(\varphi)+ +p_{T2.j-G6.j}(\varphi)+p_{G6.j-T3.j}(\varphi)+ +p_{T3.j-G8.j}(\varphi)+p_{G8.j-N.j}(\varphi). \quad (4)$$

Under condition $G_4\notin l_{T1.j\text{-}T2.j}(\varphi)$ for contour lengths $\xi'^k_{0.j}$, $\xi'^k_j(\varphi)$:

$$p'_{T1.j-T2.j}(\varphi)=p_{T1.j-G4.j}(\varphi)+p_{G4.j-T2.j}(\varphi),$$

$$\xi'^A_j(\varphi)=\xi_{1.j}(\varphi)+p'_{T1.j-T2.j}(\varphi)+p_{T1.j-T2.j}(\varphi)+ +p_{T2.j-G5.j}(\varphi)+p_{G5.j-G6.j}+p_{G6.j-G7.j}+ +p_{G7.j-G8.j}(\varphi)+p_{G8.j-N.j}(\varphi), \quad (5)$$

$$\xi'^B_j(\varphi)=\xi_{1.j}(\varphi)+p'_{T1.j-T2.j}(\varphi)+ +p_{T2.j-G6.j}(\varphi)+p_{G6.j-T3.j}(\varphi)+ +p_{T3.j-G8.j}(\varphi)+p_{G8.j-N.j}(\varphi), \quad (6)$$

where

$$p_{G0.j-G1.j}=P_{G1.j}-P_{G0.j},\; p_{G1.j-G2.j}=P_{G2.j}-P_{G1.j},$$

$$p_{G2.j-G3.j}=P_{G3.j}-P_{G2.j},\; p_{G5.j-G6.j}=P_{G6.j}-P_{G5.j},$$

$$p_{G6.j-G7.j}=P_{G7.j}-P_{G6.j},\; p_{G3.j-T1.j}(\varphi)=P_{T1.j}(\varphi)-P_{G3.j},$$

$$p_{T2.j-G5.j}(\varphi)=P_{G5.j}-P_{T2.j}(\varphi),$$

$$p_{G6.j-T3.j}(\varphi)=P_{T3.j}(\varphi)-P_{G6.j},$$

$$p_{G7.j-G8.j}(\varphi)=P_{G8.j}(\varphi)-P_{G7.j},$$

$$p_{T3.j-G8.j}(\varphi)=P_{G8.j}(\varphi)-P_{T3.j}(\varphi),$$

$$p_{G8.j-N.j}(\varphi)=P_{N.j}(\varphi)-P_{G8.j}(\varphi).$$

To determine the length of segments $p_{i.j}$ at the initial reference moment (φ=0°), the same dependences are applied as when determining segments $p_{i.j}(\varphi)$ at φ=0°.

The values of the piecewise function of the required feed of the ideal thread $P'(\varphi)$ according to expressions from [5] were determined for intervals according to the cyclogram of the machine MF-7923D, Juki.

4. 5. Determining the position functions of thread take-ups $T_1(\varphi)$ and $T_2(\varphi)$

To determine the variable parameters of two moving thread take-ups $T_1(\varphi)$ та $T_2(\varphi)$ ($T_3(\varphi)$), the methodology from [25] was applied.

The position of the crank O_1A (Fig. 5, *a*) in the spatial kinematic chain (with kinematic pairs: O_1, A, B, O_2), where the driven link is the thread take-up T_1, is determined by the angle $\varphi_{M1\text{-}0}$ [25]. Radius vectors of kinematic pairs in PSK: P_{O1}, P_A, P_B, P_{O2}. The radius vector of the eye of the thread take-up T_1 is denoted as P_{T1}. Accordingly, the links of the mechanism (Fig. 5, *a*) taking into account the direction in the vector designation: crank O_1A – P_{O1-A}, connecting rod AB – P_{A-B}, rocker arm O_2B – P_{O2-B} and thread take-up $P_{O2\text{-}T1}$. We denote the lengths (or modules) of the specified vectors as $l_{i\text{-}j}$.

A discrete variable that describes the movement of the main shaft together with cranks O_1A and O_3D:

$$\varphi:=\varphi_0,\varphi_{0+1}+\Delta\varphi_1\ldots\varphi_{\max}. \quad (7)$$

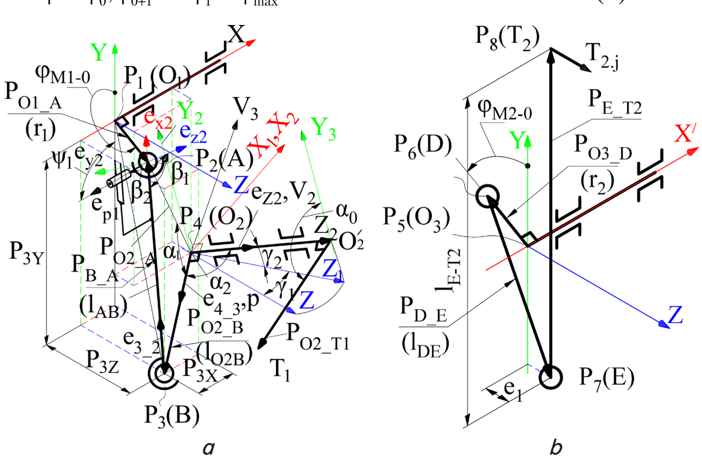


Fig. 5. Vector calculation diagram of functional groups in the mechanism: *a* – spatial crank-rocker kinematic chain O_1ABO_2 of thread take-up $T_{1.j}$; *b* – flat crank-sliding kinematic chain O_3DE of the needle mechanism and thread take-up $T_{2.j}$

The radius vector of the kinematic pair P_3 is determined on the basis of affine transformations [25].

Hence, the radius vector of the thread take-up hole P_{T1}:

$$P_{T1}(\varphi):=P_{O2'}+\rho_K\left(P_{O2-B}(\varphi),T_Z(\alpha_3),l_{O2'-T1}\right),$$

where the radius vector $P_{O2'}$ is a vector that determines the position of point $O_{2'}$ on the rocker arm shaft; $l_{O2'-T1}$ – the shortest distance between points $O_{2'}$ and T_1; α_3 is the angle between vectors P_{O2-B} and $P_{O2'-T1}$; $T_Z(\alpha_3)$ is the rotation matrix around the ordinate axis; ρ_K is a special function in the Mathcad program for calculating free vectors:

$$\rho_K(r_1,T_K,l_2):=T_K\cdot Ort(r_1)\cdot l_2,$$

where T_K is the rotation matrix around one of the coordinate axes; $Ort(r_1)$ is the ort of the returned vector; l_2 is the modulus of the vector after rotation:

$$Ort(r_1):=\frac{r_1}{|r_1|}.$$

The function of position $\psi(\varphi)$ of the thread take-up $T_{1.j}$ as the angle of oscillation of the rocker O_2B:

$$\psi(\varphi):=T\cdot\cos\left(\left|P_{O2A}(\varphi,l_{O1A})\right|,l_{O2B},l_{AB}\right). \quad (8)$$

Kinematic chain with the leading link of the crank O_3D (Fig. 5, *b*), with the driven link of the thread take-up $T_{2.j}$. The position of the crank O_3D is determined by the angle $\varphi_{M2.}$

The rotating kinematic pairs of the mechanism are marked O_3, D, E, and the radii vectors of the kinematic pairs P_{O3}, P_D, P_E, and the eyelet of the thread take-up $T_{2.j}$ are marked P_{T2}. Then the kinematic chain is in vector form (Fig. 5, *b*): the crank P_{O3-D}, the connecting rod P_{D-E}, and the vector of the loop of the thread take-up – $P_{E\text{-}T2}$.

A variable that describes the movement of the driving crank O_3D, taking into account its position on the main shaft:

$$\varphi_{M2}(\varphi):=\varphi+\varphi_{M2-0}. \quad (9)$$

In expression (9), $\varphi_{M2\text{-}0}$ is the initial angle of setting the driving crank 4.

The radius vector of the kinematic pair P_D is determined from the following expression:

$$P_D(\varphi):=P_{O3}+\rho_K\left(e_Y,T_X\left(f_{M2}(\varphi)\right),l_{O3-D}\right), \quad (10)$$

where $T_X(f_{M2}(\varphi))$ is the rotation matrix around the abscissa axis by the angle $f_{M2}(\varphi)$:

$$T_X\left(f_{M2}(\varphi)\right):=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\left(f_{M2}(\varphi)\right) & -\sin\left(f_{M2}(\varphi)\right)\\ 0 & \sin\left(f_{M2}(\varphi)\right) & \cos\left(f_{M2}(\varphi)\right)\end{pmatrix}.$$

The radius vector of the kinematic pair $P_E(f_1)$ is found using the following expression:

$$P_E(\varphi):=$$
$$=\begin{bmatrix}P_{O3X}\\ l_{O3-D}\cdot\cos\left(f_{M2}(\varphi)\right)-l_{D-E}\sqrt{1-\left(\frac{l_{O3D}\cdot\sin\left(f_{M2}(\varphi)-e_1\right)}{l_{D-E}}\right)^2}\\ e_1\end{bmatrix}, \quad (11)$$

where e_1 is the desaxial of the mechanism (for the mechanism under study, $e_1=0$).

The radius vector of the eye of the thread take-up p_{T2} is determined from the following expression:

$$p_{T2}(\varphi) := p_E(\varphi) + e_Y \cdot l_{E-T2}. \quad (12)$$

The parameters of variation of the NTTM mechanism, which are taken from the indicated adjustment zones and possible values of the lengths of NTTM links, are given in Table 3.

Listed in Table 3, the intervals of adjustable parameters will be applied to determine their influence on the laws of movement of thread take-up $T_{ij}(\varphi)$ and the actual thread take-up function for each needle $P(\varphi)_j^k$.

Table 3

Ranges of changing adjustable parameters

Adjustable parameter	Designation	MF-7923D Juki
		Value range
Eccentric radius O_1A	r_1, mm	4÷5
Crank radius O_3D	r_2, mm	15.5÷16.5
Rocker arm length O_2B	l_{O_2B}, mm	20÷23
The amount of displacement of the rocker arm AB from the axis of the main shaft	z, mm	−10÷10
Phase angle between eccentric O_1A and crank O_3D	$\Delta\varphi$, deg.	−20÷20

Note: $\Delta\varphi=\varphi_{M1-0}-\varphi_{M2-0}$.

4. 6. Determining the influence of the spatial coordinate system on the thread take-up function

In order to check the accuracy of calculations in three-dimensional coordinate systems, a comparison of the laws of actual thread take-up $P(\varphi)$ in XY and XYZ coordinates, respectively $P_{2D}(\varphi)$ and $P_{3D}(\varphi)$ was performed. The functions of actual thread take-up are determined from expressions (1) to (6). During the calculations in the plane coordinate system of thread guides and thread take-ups (Table 2), the third coordinate was assumed equal to zero, i.e., $z(w)=0$.

Differences in the values $\Delta P(\varphi)$ of the function $P_{2D}(\varphi)$ and $P_{3D}(\varphi)$ according to the expression:

$$\Delta P(\varphi) = P_{3D}(\varphi) - P_{2D}(\varphi). \quad (13)$$

The calculation of the thread take-up function and the determination of the deviations were carried out for the feeding circuit "A" and one needle in order to evaluate the deviations in different coordinate systems and check the correctness of results in the two-dimensional coordinate system.

5. Results of investigating the influence of kinematic parameters on the function of actual thread take-up

5. 1. Characteristics of the influence of control parameters on the value of the actual take-up function

According to the values of variation parameters (Table 3), the characteristics of the influence of the functional groups of the thread take-up mechanism on the law of movement of the thread take-ups are obtained, which are represented by the spatial plots in Fig. 6.

Fig. 7 shows the influence of each individual kinematic parameter (r_1, r_2, l_{O_2B} z, $\Delta\varphi$) on the function $P(\varphi)$. For comparison, the curve of the values of the required feed for the far needle $P'(\varphi)_3$ at the value of the material thickness $m=3$ mm is also given.

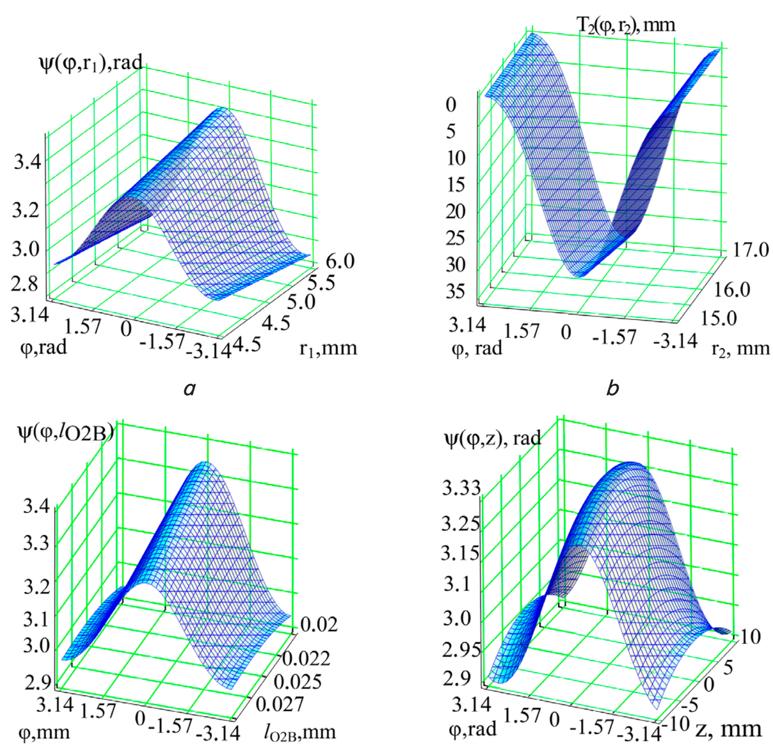


Fig. 6. Spatial charts of kinematic characteristics of the functional groups O_1ABO_2 and O_3DE of a needle thread take-up mechanism when the adjustable parameters are varied: *a* – r_1; *b* – r_2; *c* – l_{O_2B}; *r* – z

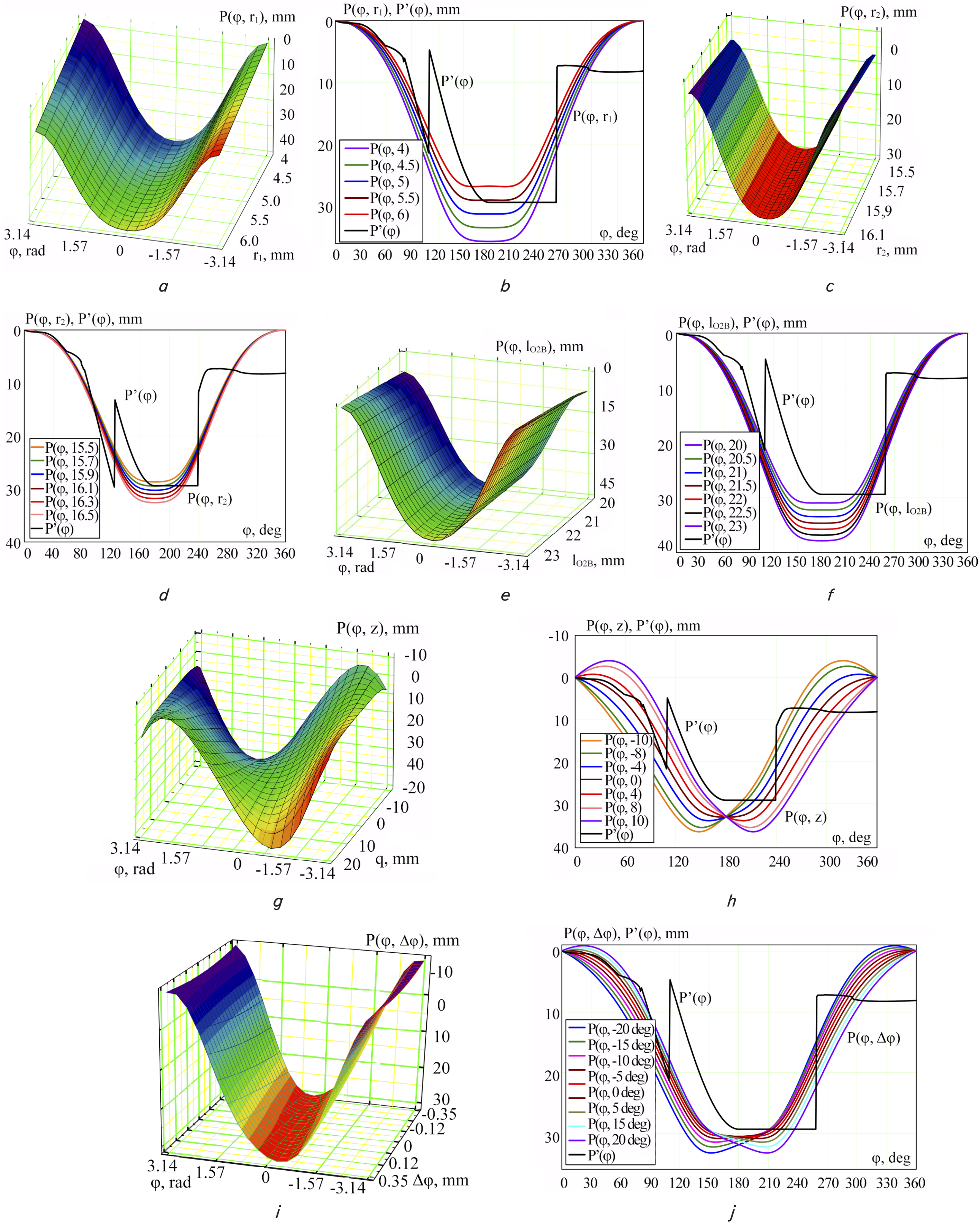


Fig. 7. Spatial charts and diagrams of values of the actual $P(\varphi)$ and the required $P'(\varphi)$ thread take-up at the following values of parameters: *a, b* – r_1; *c, d* – r_2; *e, f* – l_{O_2B}; *g, h* – z; *i, j* – $\Delta\varphi$

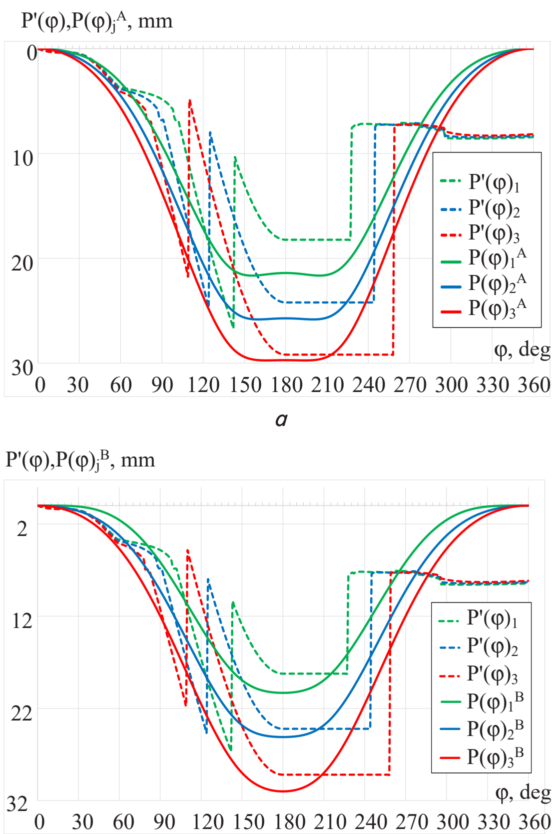
The resulting spatial charts and diagrams of the required and actual feed of threads $P(\varphi)$ and $P'(\varphi)$ show the nature of influence on them of the laws of motion of thread take-up $T_{i,j}(\varphi)$ depending on the value of kinematic parameters in the specified ranges (Table 3).

5. 2. Parameters of the perfect thread take-up function in the Juki MF-7923D sewing machine for "A" and "B" contours

According to the given values of NTTM parameters (Tables 1, 3), thread take-up diagrams for different needles for different filling contours "A" and "B" were constructed (Fig. 8).

Our thread take-up diagrams characterize the amount and law of feeding of an ideal NTTM thread of this type depending on the contours of feeding the threads "A" and "B" for each needle when forming a stitch of type 407.

In the future, these results can be used to take into account the physical and mechanical properties of threads in the function of real thread take-up, as well as to devise recommendations for adjusting and designing new mechanisms.

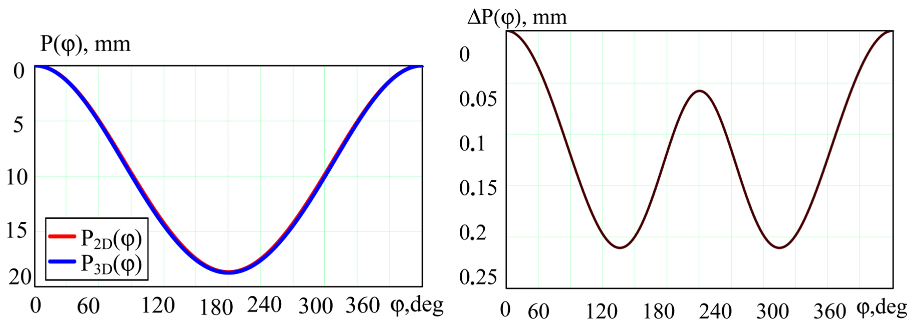


b

Fig. 8. Diagrams of thread take-up according to the feeding contour: *a* – contour "A"; *b* – contour "B"; $P'(\varphi)_j$ – diagrams of the function of the required thread take-up of *j*-th needles; $P(\varphi)_j^A$ – diagrams of the function of the actual thread take-up of *j*-th needles; $P'(\varphi)_j$ – diagrams of the function of the required thread take-up of *j*-th needles; $P(\varphi)_j^B$ – diagrams of the function of the actual thread take-up of *j*-th needles

5. 3. Functions of the actual and required thread take-up in the spatial and flat coordinate system

The obtained values of the actual thread take-up functions $P_{2D}(\varphi)$ and $P_{3D}(\varphi)$ with the set adjustment parameters for the near needle j=1 in the XY and XYZ coordinates and the difference in their values – $\Delta P(\varphi)$ – are shown in Fig. 9.



a *b*

Fig. 9. Plots of the actual thread take-up function for the first needle (j=1): *a* – $P_{2D}(\varphi)$ – flat system XY, $P_{3D}(\varphi)$ – spatial system XYZ; *b* – the difference of the function of the actual thread take-up $\Delta P(\varphi)$

The resulting diagrams of the thread take-up functions show how the choice of the coordinate system in the calculation model of a thread take-up mechanism of lever-type sewing machines affects the accuracy of the calculation.

6. Discussion of results based on investigating the influence of parameters on the actual thread take-up

The results of varying the kinematic parameters r_1, r_2, l_{O2B}, z, $\Delta\varphi$ in NTTM showed that the nature of their influence on the law of actual thread take-up $P(\varphi)$ (Fig. 7) corresponds to the law of movement of thread take-ups $T_1(\varphi)$, $T_2(\varphi)$ (Fig. 6). Thus, parameters r_1, r_2, l_{O2B} directly affect the value of the actual thread take-up $P(\varphi)$ (Fig. 7, *a–e*) since they change only the value of thread take-ups T_{1j} and T_{2j}. An increase in the radius r_1 of the eccentric in the range of 4÷6 mm leads to an increase in the angle of oscillation $\psi(\varphi)$ of the thread take-up T_{2j} (Fig. 6, *a*) and an increase in the maximum values of the function $P(\varphi)$ by 10 mm (Fig. 7, *a, b*). A similar sequence is observed for the parameter r_2 (Fig. 6, *b*, 7, *c, d*), and conversely, an increase in the length of the rocker l_{O2B} leads to a decrease in the angle of oscillation of the thread take-up $\psi(\varphi)$ (Fig. 6, *c*) and a decrease in the values of $P(\varphi)$ (Fig. 7, *d, f*).

Changing the values of the kinematic parameters within the NTTM adjustments of the MF-7923D machine by Δr_1=2 mm, Δr_2=1 mm, Δl_{O_2B}=3 mm leads to a change in the value of the actual thread take-up $\Delta P(\varphi)$, respectively, by 10 mm, 4 mm, and –7 mm.

The change in parameters z and $\Delta\varphi$, respectively, mainly affects the law $\psi(\varphi)$ of the thread take-up T_1 (Fig. 6, *d*, 7, *e, g*) and the mutual synchronicity of the thread take-ups T_{1j} and T_{2j}, which is reflected in the nature of the law of thread take-up $P(\varphi)$ (Fig. 7, *f, g*). However, the parameter z has a greater influence on the law of actual thread take-up $P(\varphi)$ (Fig. 7, *f, g*) than the asynchrony of the cranks r_1 and r_2 – $\Delta\varphi$ (Fig. 7, *h, i*). It should be noted that the displacement with a negative sign – z (Fig. 1) by a value of only 2 mm ensures a greater correspondence of the actual thread take-up $P(\varphi)$ to the required take-up $P'(\varphi)$.

Thus, it was established that the values of parameters $\pm z$=0÷10 mm, $\Delta\varphi$=±20° lead to a change in the value and law of thread take-up $\Delta P(\varphi)$, respectively, by 3÷3.5 mm and its asymmetry $\Delta\varphi$=±28÷32°.

It is advisable to take into account parameter z in the range of z=–2÷–5 mm when developing nomograms for adjusting the NTTM of sewing machines of a similar structure. This ensures a sufficient correspondence between the actual thread take-up $P(\varphi)$ and the required take-up $P'(\varphi)$ when the thickness of the materials is from 3 to 5 mm.

These parameters will be useful for more precise adjustment of the sewing machine, which should be taken into account in the machine adjustment nomograms [5].

At the same time, this result can be applied only for low-stretch threads with physical and mechanical properties that are close to an ideal thread. For elastic threads, it is necessary to take into account the parameters of deformation and relaxation, which requires the determination of the instantaneous angles of coverage of the thread guides and thread take-ups with the thread and may be the subject of further research.

Analysis of the feed contours and their laws $P(\varphi)_j$ and $P(\varphi)_j$ NTTM revealed that the feed contour "A" provides a higher correspondence between the actual thread take-up and the required take-up $P'(\varphi)j$ (curves $P(\varphi)_{1,2,3}$ in Fig. 8, *a*). At the same time, the feeding circuit "B" implements the laws of actual thread take-up $P(\varphi)_j$ (Fig. 8, *b*) in which there are no horizontal sections, and the amount of fed thread is greater – $P(\varphi)_j > P(\varphi)_j$ .With the feeding circuit "B", more thread is fed, which leads to a tightening of the stitch with smaller deformations of the thread, which allows the use of low-stretch threads.

The use of different thread take-up circuits in one machine makes it possible to solve the issue of stitching with different types of threads. At the same time, this indicates the imperfection of NTTM, where the fight against thread deformation is carried out by increasing the amount of supplied thread, which is characteristic of all types of NTTMs [16].

Installation of an additional thread clamp $G_{7.j}$ (Fig. 3, *a*) on the machine body (Fig. 2, *a*) and the needle guide (Fig. 2, *b*), respectively, in the take-up circuit "A" and "B" (Fig. 3, *b*) leads to a different length of the circuit $p_{G0.j\text{-}G7.j}(\varphi) < p^{B}_{G0.j\text{-}G7.j}(\varphi)$. Thus, in the process of feeding the NTTM thread, sections $p_{G5.j\text{-}G6.j}$, $p_{G6.j\text{-}G7.j}$ of the circuit "A" and the section $p_{G7.j\text{-}G8.j}$ in the contour "B" remain unchanged in length – const. At the same time, in the circuit "B", the section of the circuit $p_{G6.j\text{-}G7.j}(\varphi)$ depends on the law of movement of the needle guide $S(\varphi) = T_2(\varphi)$. The presence of thread clamp $G_{7.j}$ makes it possible to reduce the effect of thread relaxation, which occurs as a result of thread deformation due to the discrepancy between the actual thread take-up and the required one ($P(\varphi) < P'(\varphi)$). It is obvious that the pressing force of the thread clamp $G_{7.j}$ determines the degree of minimum tension of the needle threads in the stitch and provides the necessary structure of the stitch type [1]. However, the quantitative influence of the thread clamp $G_{7.j}$ on the value of $P(\varphi)$ for different take-up circuits "A" and "B" can be determined only by considering the balance of forces acting on elementary sections of the thread circuit according to the methodology from [5]. This may be the subject of further research.

Our studies on the influence of a spatial coordinate system of the feed contour on the actual thread take-up function $P(\varphi)$ ($P_{2D}(\varphi)$ and $P_{3D}(\varphi)$, Fig. 9) show that the maximum difference in values is approximately $\Delta P(\varphi) \approx 0.2$ mm (Fig. 9) it was found that the z coordinate in the calculations has almost no effect on the designation of the function $P(\varphi)$, and its influence on $\Delta P(\varphi)$ is much smaller than the amount of thread deformation that occurs during the operation of NTTM. Therefore, in the calculations of typical NTTMs of the lever type, simplifications can be applied with a fairly high accuracy.

It is worth noting that the research was carried out for thread take-up mechanisms, where the coordinates of thread guides and thread take-ups of a specific needle almost lie in the same plane. This makes it possible to simplify calculation methodology, but in other cases, for example, in cam mechanisms, this approach may be incorrect.

Our results regarding the analysis of the feed contours of these machines cannot be directly applied to the whole range of similar machines, but only have the character of general recommendations. Therefore, in the future, it is necessary to determine the common parameters in the mechanisms of machines of this type and devise appropriate recommendations for their adjustment and design.

Taking into account the physical properties of threads in further studies will significantly increase the quality and accuracy of results. However, due to the large assortment and wide range of properties of sewing threads, conducting such a study will be more time-consuming.

It is expected that the results of the research will allow us to optimize the parameters for a thread take-up mechanism (NTTM) both when designing new equipment and when adjusting existing machines. They can also be used in the design of special automated equipment for the production of pre-forms based on 2D textile, knitted, non-woven, and other materials.

7. Conclusions

1. Adjustment of the kinematic parameters r_1, r_2, l_{O_2B} is necessary when changing the amount of thread take-up. The correspondence of the characteristics of the feed laws $P(\varphi)$ and $P'(\varphi)$ is achieved by the parameters z and $\Delta\varphi$, which take values in the range from 0 to −5 mm and from 0 to −20°, respectively. These parameters make it possible to configure the equipment to work with material thicknesses from 0 to 5 mm. The obtained regularities of influence by $\pm z$ can be applied to design special thread take-up mechanisms that respond to a sharp change in the thickness of materials when creating 3D frame parts for pre-forms.

2. Despite the use of different thread take-up contours in typical NTTM lever structure, the task of increasing the correspondence of the actual thread take-up $P(\varphi)$ to the required take-up $P'(\varphi)$ is only partially solved, which indicates the imperfection of these mechanism structures.

3. Our results confirm the possibility of applying simplifications in NTTM calculations in the form of a flat coordinate system since the error, compared to taking into account the spatial location of their elements, is up to 2 %, which is ten times smaller than the amount of thread deformation in the general thread take-up circuit.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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