TOPOLOGICAL ANALYSIS AND SYNTHESIS OF MACHINE CHAIN STITCHES

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Abstract: *The topological analysis of chain stitches of classes 100, 400, 500, 600 and 800 is performed in the work; the general regularities of their formation are established by dividing them into typical structural elements. Also provide recommendations for creating new and potentially possible types of stitches with the development of graphs and calculation of thread consumption for stitches. The method was used in the work, which includes the main stages of topological analysis and synthesis, namely: formation of problems, division of objects (stitches) into elements, construction of models (morphological matrices), synthesis of object variants, and selection of the most rational variants, application of the method of graphs. The result is a generalized hierarchy of the structure of chain stitches of different classes, which are formed by structural elements (loops, broaches and applying thread or sketches [1]) and possible combinations of stitch types. A code record of the structure of stitch elements in the form of routes of 3D-graphs that determine the geometric length of each thread (excluding the properties of the material and threads) is also obtained. Matrixes of stitch configurations are obtained, regularities of formation of new types of stitches of different classes are revealed and the graph-generator of new types of stitches is offered. Regularities of formation of structures of chain stitches of different classes on the basis of development of the hierarchical scheme of structural elements of chain stitches of different classes, morphological matrices and graphs of formation of chain stitches are also revealed. The method of structural analysis and synthesis of new types of stitches is offered. The obtained results can be used for the synthesis of new or potentially possible types of stitches, determining the cost of sewing threads in the stitch depending on the technological parameters of the stitch and materials (stitch length, thickness of materials under the presser foot of the sewing machine, width of overlock stitch, etc.) stitch quality forecasting and the use of initial data for the design and adjustment of sewing machine mechanisms.*

Keywords: *structures of chain stitches, structural analysis, determination of thread length in stitch, 3D stitch graph, stitch intensity matrix, morphological matrix of stitches, chain stitch, chain stitch generator.*

1 INTRODUCTION

Chain stitches of classes 100, 400, 500, 600 and 800 are sold in a wide range of sewing machines, which are manufactured by a number of foreign companies and are designed for processing and stitching fabrics and knitwear. Each class of stitches includes several types of stitches in accordance with 100 class includes 7 types, 400 class - 17 types, 500 class - 16 types, 600 class - 9 types, 800 class - 6 types, which are formed by a combination of individual types of stitches 300 - 600 classes [2]. In addition to the standard types of stitches, there are many other types of stitches that are not included in the general classification and are known from other sources and patents [3-12] and so on. Each type of stitch differs not only in the number of threads, but also in the position of their elements in its structure. The structure of stitches is described in the literature quite fully. Among the elements of the stitch are: loop, broach, applying thread (sketches) [13-15]. The cost of the number of threads per unit stitch is determined by known methods [16-19]. Thus, in [16, 17] thread costs are defined as the sum of individual stitch elements for a certain stitch length, which allows to determine the costs of upper and lower threads, as well as its total value, in the literature [18] thread costs in stitch type 504 are determined by using geometric modeling, at the same time in the literature [19] the algorithm for determining the length of the thread for different types of stitches without explaining the essence of the method of determination.

The difficulty of calculating the costs in one stitch, as a discrete element of the stitch, is that when determining the total cost in the stitch, the error of the length of the thread of each stitch accumulates in arithmetic progression according to the number of stitches, so in such cases deformation of materials by stitch compression [16]. The leading German companies Amann Saba, Gutermann and Epic Coats (UK) offer thread consumption calculations for the main types of stitches, which take into account the properties of the threads, the number of threads and needles, and so on.

The description of the processes of chain stitch formation in the available literature [15, 20] is given only for a few types, and in [15] the author presents in the form of graphs and matrices of adjacency the process of forming the main types of overedge, multi-thred and blind chain stitches, them to analyze the structure and process of formation of any type of stitch.

Issues of synthesis and regulation of the main mechanisms (needles, loops, expanders, top cover spreader, rack and knives) in the literature are covered quite fully. At the same time, there is no general recommendation for the synthesis and selection of the structure of the thread feed mechanisms for a particular stitch type. There are also no recommendations for their adjustment in accordance with the type of thread, materials, stitch structure, its parameters, etc.

2 STATEMENT OF THE TASK

Within the limits of research to carry out the morphological analysis of structures of chain stitches of 100, 400, 500, 600 and 800 classes as a result of which to receive morphological matrices and structural formulas of stitches in the form of routes of 3D-graphs. Obtain formulas for summarizing the routes of 3D-graphs depending on the parameters of the stitch (number of needle threads, the position of the thread weaves on the material and its thickness, zigzag width, etc.), which will obtain generalized formulas for determining the cost of each thread per stitch and graphical computer structure modeling new types of stitches.

It is necessary to establish the logical sequence of formation and hierarchical subordination of each element of a stitch and to reveal new communications between them that will allow to receive new types of stitches with new opportunities. The main task of this work is to develop the basics of the theory of synthesis of new structures and types of chain machine stitches with given geometric properties and design of equipment for their implementation.

3 RESEARCH RESULTS

Class 100 combines single-thread chain stitches (101, 103, 104, 105, 107, 108 types) and double-thread (102 type), which are formed by a needle (straight or arcuate) and an expander [2].

Class 400 combines many thread chain stitches, which are formed by two threads (needle thread and loop thread - 401, 404, 409, 411-417 types), three threads (two needle threads and one loop thread - 402, 405, 406 types), four threads (three needle and one thread of the looper - 403, 407 types) and five threads (two needle, two threads of the looper and cover thread - 408 type), four needle and one thread of the looper - 410 type.

Class 500 combines overedge chain stitches, which are formed by a single thread or groups of threads: single-thread (501, 513 types - formed only by a needle thread); double-threaded (502, 503 types - formed by the threads of the needle and the lower loop); three-thread (504, 505 types - formed by a needle thread and two threads of the lower and upper loops and multi-line in the process of their formation involved two needle threads - 510, 511 types, two needle and two threads of the lower loop - 508, 509, 521 types) , two needle threads and two looper threads (506, 507, 512, 514 types).

Class 600 combines cover chain stitches, which as a result of grinding cover both surfaces of materials with a cover thread (top cover spreader), which are formed by three threads (two needle and one loop thread - type 601), four threads (two needle, one and one loop thread and cover thread - 602 type), five threads (two needle, one loop of thread and two cover threads - 603 type; three needle and one loop of thread and cover thread 605 type), six threads (three needle, one thread of loop and two cover threads – 604; four needle, one thread of loop and one cover thread - 607, 609 threads; needle, one loop of thread and two cover threads - 608 type) and nine threads (four needle threads, four threads of loopholes and one cover thread - 606 type).

Class 800 - combines different types of chain and shuttle stitches 801 (515) formed by a combination of 401 and 503 stitch types; 802 (516) - 401 and 504 types; 803 (517) - 301 and 504; 804 (518) - 301 and 503, 805 (519) - 401 and 602 types; 806 (520) is formed by two stitches type 401 and type 602.

The analysis of stitch types of class 800 shows that they are obtained by combining individual types of stitches and complement the class 500 stitches [20]. Since the 800^{th} class of stitches belongs to the highest hierarchy of stitches, many of its elements will be covered when considering the stitch types of other classes.

Presence of broaches, sketches, loops of threads (needle, threads of loopers, top cover spreader), or the report of a zigzag of a stitch allow to allocate characteristic elemental contours of a thread. In general, in the structure of each type of stitch, you can select the characteristic contours of each thread, which are part of the stitches (Figure 1) determining the rational parameters of the mechanism.

The designation of the contours corresponds to [2], the contours of the thread 1…18 (loops) are formed by a needle thread, the contours of the thread are denoted by lowercase letters ai and bi (broaches) are formed by threads, respectively lower and upper loop, the contours are denoted by letters *Z, Yi* (sketches), correspond to the threads of the decomposer, here are also the contours *a3, c3* and *a4, c4* of the proposed types of stitches [3-11].

For multi-row (multi-needle) stitches as the identifier of interweaving of needle threads of the main element "1" (Figure 1) with other threads, the designation of the number of pairs of inter-loop needle rows is introduced: $i = 0, 1, 2, 3…n$, $j = 0, 1, 2, 3…p$ with the distance h between the i-th and j-th needle rows and the parameter corresponds to the broach formed by the branches of the loop, which is covered by the top of the loop of the thread. Accordingly, the j parameter corresponds to the outline (interlooping connection) of branches that cover with their vertices the branches of the loops of other threads. Interweaving rows correspond to the interweaving of the number of loops $i + 1$ and $j + 1$ needle threads.

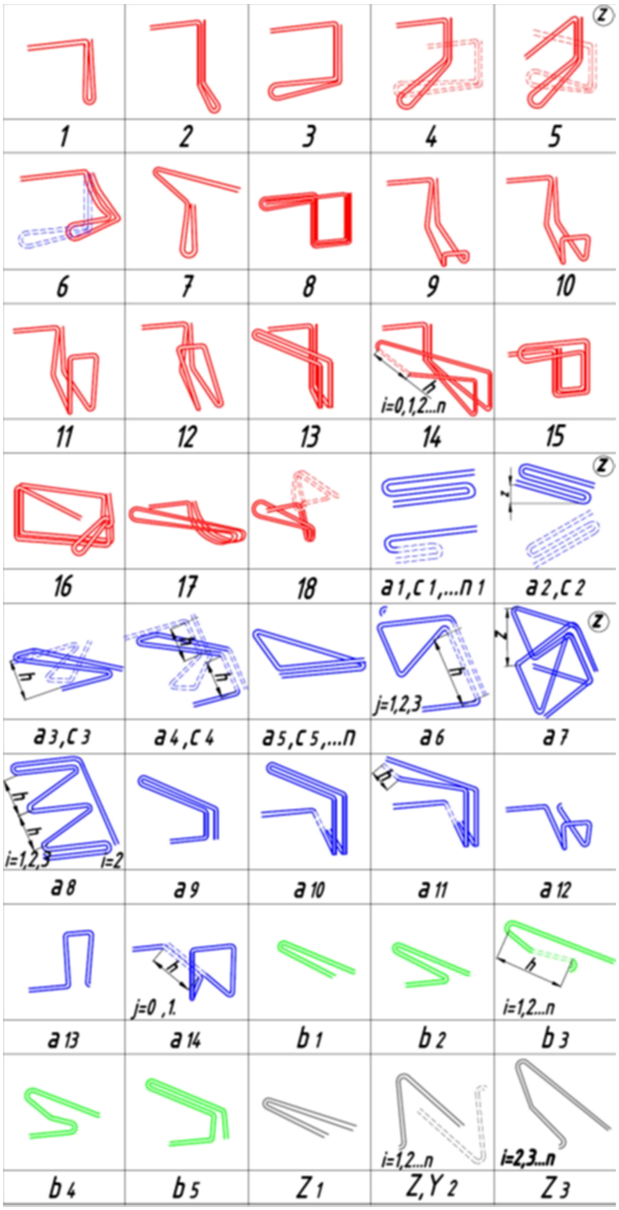


Figure 1 Structural elements of chain stitches of types 100, 400, 500, 600, 800: *1…18* - needle thread (loop); *a1-14* - threads of the lower loop (broaches); *b1-5* - threads of the upper loop (broaches), *Z1-3* - threads of the top cover spreader (sketches)

Based on the analysis of contour elements, the classification of heredity of their formation from elementary to complex is proposed, respectively for needle thread, lower loop thread, upper loop thread and top cover spreader (Figures 2-4) here are also block diagrams with coded notation of structural elements.

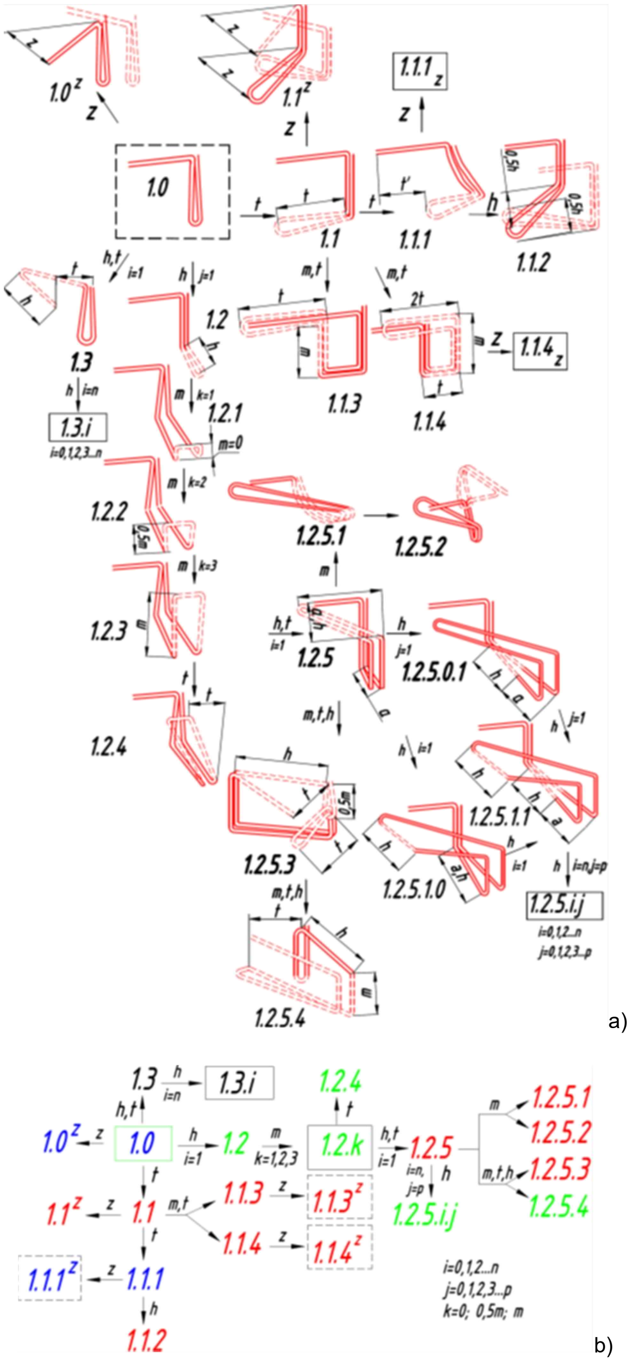
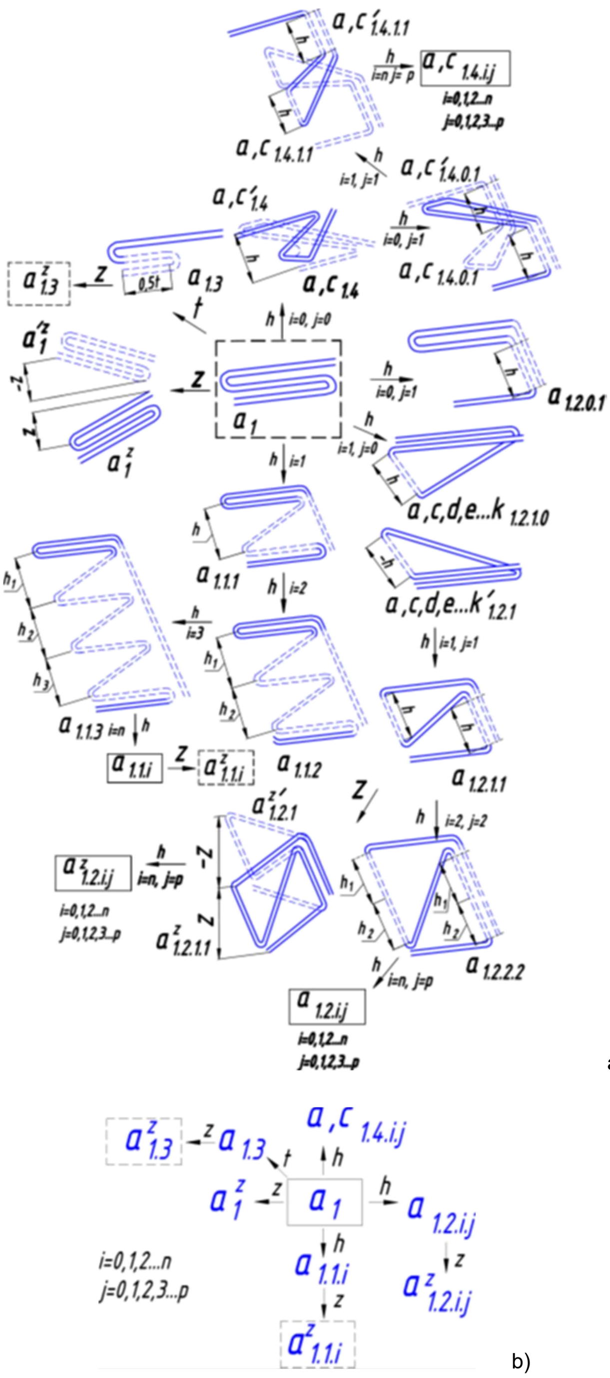


Figure 2 Hierarchical scheme of formation of the elements of the contour of the needle thread of chain stitches: a) graphical - structural representation of the elements; b) is a block diagram of the stitch element

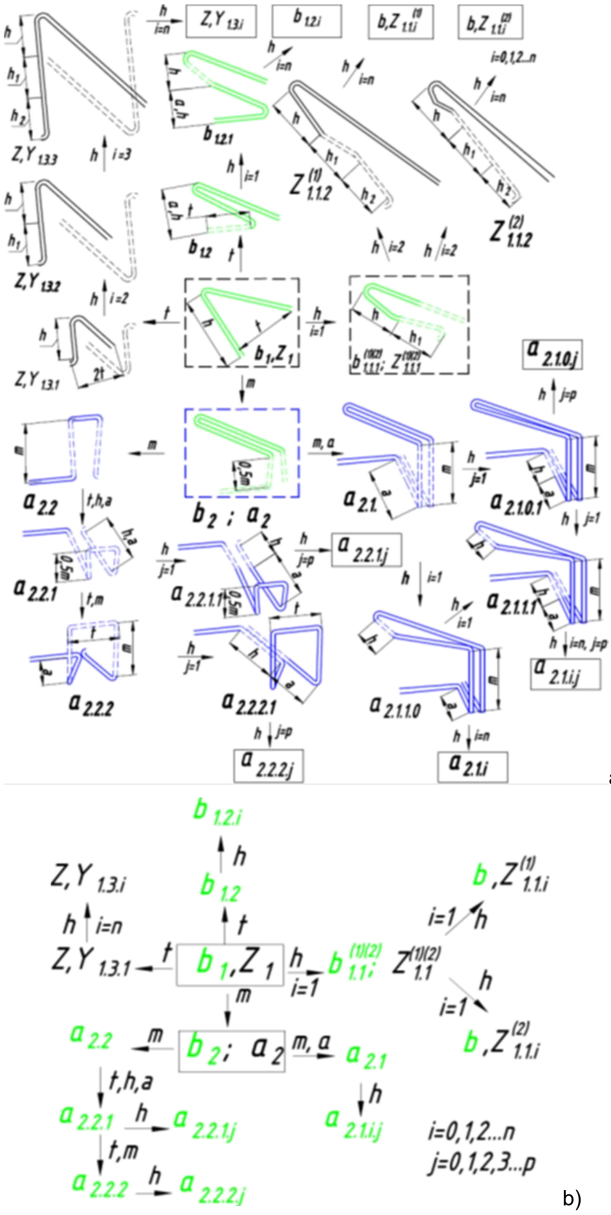
The hierarchical and structural diagrams above the expansion route (indicated by the arrow) show the modifiers (h is the distance between adjacent needle rows, *m* is the thickness of the materials, *t* is the stitch length, *z* is the width of the zigzag), below it is the quantitative characteristic of the modifier. In addition, for several elements of the stitch found structural formulas that reduce the complex contour of the element into a simple (basic) by reducing the *i-th, j-th* parameter to zero (in the diagrams of Figures 2-4 are surrounded by rectangles with a solid line). In turn, the increase of the *i-th, j-th* parameter, leads to the formation of new types of stitches.



a)

b)

Figure 3 Hierarchical scheme of formation of elements of the contour of the thread of the lower loop of chain stitches: a) graphical - structural representation of the elements; b) block diagram of stitch elements



a)

b)

Figure 4 Hierarchical diagram of the elements of the contour of the threads of the lower and upper loop and the top cover spreader of chain stitches: a) graphically - structured representation of the elements; b) block diagram of stitch elements

The contour elements of the needle thread (Figure 2) do not have repeatability among the elements of other stitch threads due to the fact that the thread is passed through a material that is characteristic only of the needle thread. Element *1.2.i.j* is obtained by modifying from element *1.2.5* parameter *h* with the possibility of combining both modifiers of the *i-th, j-th* parameter. In turn, the element *1.2.i* also forms a series of new stitches with a covering thread (600 class) formed by sketching the loop of the extreme needle thread while increasing the number of interneedle rows, ie the parameter *h, i = 2, 3...n*. It is established that some elements of the needle thread contour can be modified due to zigzag *z - 1.1.1Z* and *1.1.3Z 1.1.4Z*, which allows the formation of a zigzag stitch, respectively, stitches of 400 and 100 classes (new elements are surrounded by rectangles with a dashed line Figure 2). At the same time, the element *a1* (Figure 3) of the contour of the thread of the lower loop in the formation of derived elements forms a number of elements that are easily folded into the base (*a1*) by resetting the parameters *i* and *j*. Elements *1.1.1 - 1.1.3* formed by the structural formula of summary *1.1.i at i = 1, 2, 3* are used in stitches of the corresponding types 406, 407, and 410. The formation of new types of stitches is possible by increasing the number of loops of needle threads of the base element *1.0* and the *i-th* parameter. In turn, the elements *1.2.1.1, 1.2.2.2* formed by the structural formula of summary 1*.2.ij* when *i = j* are used in stitches of the corresponding types 402, 403. However, technologically it is possible to form stitches by increasing these parameters, as well as changing their different number (ie. *i ≠ j*). This confirmation is the element *1.2.1.0*, which is formed only by the *i-th* parameter (*i = 1, j = 0*) and applied in a stitch of type 606. The new element *1.2.0.1* can be formed by the inverse combination *i = 0, j = 1* and can form new types of stitches. The elements formed by *1.4.ij* were used in a number of stitches proposed by the authors (Figure 5) [3-11], the peculiarity of the process of formation of these stitches is that the process of capturing loops of needle threads ("loop loops") occurs simultaneously on both sides of the loop a number of needle threads. The introduction of loops of needle threads occurs in opposite loops formed by the threads of the looper, this allows you to significantly increase the width of the stitch and increase its elasticity.

New elements of the lower loop loop contour can be achieved with the zigzag modifier *z - aZ1.1.i* and *aZ1.3* (new elements are surrounded by rectangles with a dashed line Figure 3), which allows the formation of zigzag stitches in accordance with elements *1.0Z* and *1.1.1Z* 400 class.

Instead, the element *b1* of the upper loop thread in terms of location and size and shape corresponds to the element *Z1* of the unfolding thread, the same pattern is observed for derived elements *b1.1.1* (*Z1.1.1*). The elements are formed by a structural formula *b, Z (1) 1.1.i* and *b, Z (2) 1.1.i* differ in the position of the loop branch relative to the loops of the needle row (Figure 4). The possibility of creating new derivative elements due to the positions of the branch branch with increasing *i-th* element and >3 can also be said about the structure of *Y, Z1.3.i*. The creation of new types of stitches can be achieved by increasing the *i-th* parameter in the structure *b1.2.i* at *i >1*.

Element *b2* is identical to element *a2* - the contour of the thread of the lower loop, which in turn forms an additional 6 derivative elements of the same thread, respectively [2].

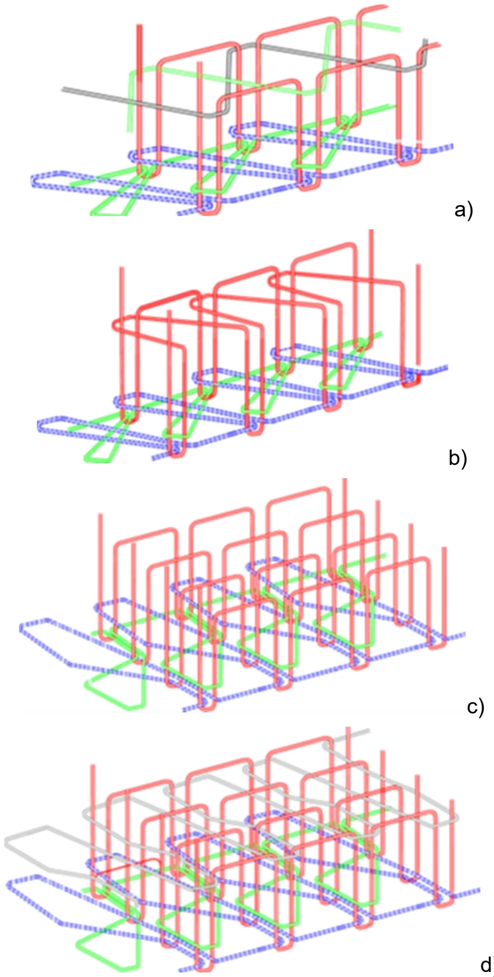


Figure 5 Structures of chain stitches based on the element *1.4.i.j*: a) six-thread cover [6]; b) four-thread cover [7]; c) six-thread flat [8]; d) semi-threaded cover [9]

The structural formula of the summary *a2.1i.j* forms elements *a2.1.0.1*, and *a2.1.1.1*, which corresponds to the elements of the thread stitch of the lower loop of types 508 and 509, the element *a2.1.1.0* is a new element that can be applied to create new types of stitches of class 500 or 800 class. When *i = 0, j = 0* is folded into the circuit *a2.1*, which is used in type 502.

In turn, the structural formulas of the reduction of the contour elements of the thread of the lower loop *a2.2.1.j* and *a2.2.2.j* at *j = 1* form derivative elements *a2.2.1.1* and *a2.2.2.1*, which are used, respectively, in the stitches of types 504 and 512. When *j = 0*, elements *a2.2.1.j* and *a2.2.2.j* are folded into elements *a2.2.1* and *a2.2.2*, which are used, respectively, in types 504 and 506. Thus, the number of elements of the needle thread - 19, the thread of the lower loop - 18, the thread of the upper loop - 5 and the thread of the unfolder - 5. Duplication of thread contour elements for these stitches is observed only in three cases - elements: *b1≡Z1, b1.2.≡ Z1.2, b1≡a2*.

In addition to changing the parameter of modifiers, as well as their number of formation of new types of stitches of the nodal structure [10-12] due to the modification of some elements of needle threads (Figure 6). The nodal structure of the stitch allows to simplify the process of formation of some stitches and the mechanisms of the lower loop, to reduce the loosening of the stitch.

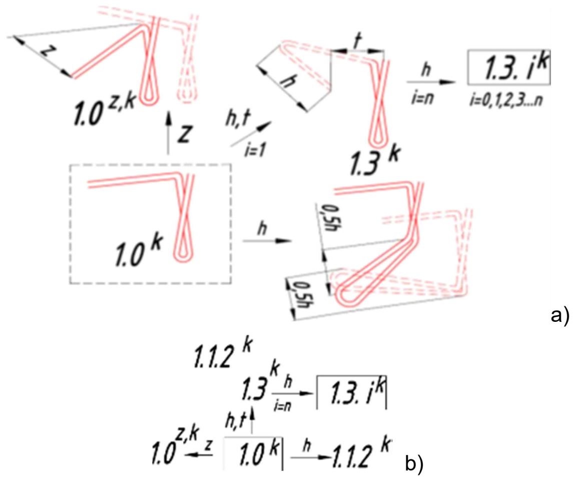


Figure 6 Hierarchical scheme of formation of contour elements of loops of a needle thread of chain stitches of knot structure: a) graphically - structural representation of elements; b) block diagram of stitch elements

Thus, increasing the number of rows of needle threads allows you to significantly expand the range of types of stitches, and the use of the knot structure of some needle threads to form new stitches knot structure. A limitation for the creation of all derived stitches is the possibility of implementing the technological process of stitch formation, ie. the possibility of reliable interaction of needles with loops.

Based on the analysis of the stitch contour element and the structure of chain stitches of classes 100, 400-600, morphological matrices of stitches are proposed, which show from which elements each stitch is formed (Tables 1-5).

From the analysis of morphological matrices it follows a possible combination of stitch elements, which is presented in the form of algorithms (Figure 7).

In turn, many combinations of thread connections of stitch elements form new types of stitches. Thus, using the basic expressions of combinatorics [21], we determine the possible number of chain stitches of each class by placing them (A_m^n).

$$A = \frac{n!}{(n-m)!} = n \cdot (n-m+1) \qquad (1)$$

Assuming *i* = *p* = *0, 1, 2, 3* we obtain for elements *a1.2 ij* and *a1.4 ij* the number of placements, the number of types of stitches 400 class, formed with the main elements of needle threads *1.0* and *1.1.1*, is 118, in its turn, zigzag - 62.

Regarding chain stitches with cover thread, taking into account the possibility of implementing the process of stitch formation and *i* = *j* = *1, 2, 3* *a1.2Zi.j* the number of placements, the number of types of stitches 600 class, formed with the main elements of needle threads *1.0*, is 192, elements *1.1.1* and *a1.3 - 3*, and element *1.3.i* - 192, ie. the total number of stitches 600 type may be 387.

Table 1 Morphological matrix of class 100 stitches

Working bodies	Stitch type						
	101	**102**	**103**	**104**	**105**	**107**	**108**
The first needle	1.1	1.1.2	1.2.5.1	1.1.3	1.2.5.2	1.1^z	1.1.4
The second needle	-	1.1.2	-	-	-	-	-

Note: z index corresponds to zigzag stitches

Table 2 Morphological matrix of stitches of class 400

Working bodies	Stitch type									
	401	**402**	**403**	**404**	**405**	**406**	**407**	**408**	**409**	**410**	**411-417**
The first needle	1.0	1.0	1.0	1.1^z	1.1^z	1.0	1.0	1.0	1.1.1	1.0	1.1^z; (1.0)*
The second needle	-	1.0	1.0	-	1.1^z	1.0	1.0	1.0	-	1.0	-
The third needle	-	-	1.0	-	-	-	1.0	-	-	1.0	-
The fourth needle	-	-	-	-	-	-	-	-	-	1.0	-
Lower looper	a1	a1.2.1.1	a1.2.2.2	a^z1	$a^z1.2.1.1$	a1.1.1	a1.1.2	a1; c1	a1.3	a1.1.3	a^z1; (a1)*
Roofing thread	-	-	-	-	-	-	-	Z1	-	-	-

Note: * element code, which is used in conjunction with the main element of the threads to form stitches of types 413 and 415

Table 3 Morphological matrix of stitches of class 500

Working bodies	Stitch type															
	501	**502**	**503**	**504**	**505**	**506**	**507**	**508**	**509**	**510**	**511**	**512**	**513**	**514**	**521**	**522**
The first needle	1.2.5	1.0	1.2.2	1.0	1.2.1	1.2	1.2	1.0	1.0	1.2.5.01	1.2.5.1.1	1.0	1.2.5.3	1.0	1.2.3	1.2.5.4
The second needle	-	-	-	-	-	1.0	1.0	1.0	1.0	1.2.5	1.2.5.1.0	1.0	-	1.0	1.2.4	-
Lower looper	-	a2.1	a2	a2.2.1	a2.2	a2.2.2	a2.2.2	a2.1.01	a2.1.1.1	-	-	a2.2.2.1	-	a2.2.2.1	-	a1.3
The upper loop	-	-	-	b2	b1.2	b1.1	b1	-	-	-	-	b1	-	b1.1	b1.2.1	-

Table 4 Morphological matrix of stitches of class 600

Working bodies	Stitch type								
	601	602	603	604	605	606	607	608	609
The first needle	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
The second needle	1.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
The third needle	-	-	-	1.0	1.0	1.0	1.0	1.0	1.0
The fourth needle	-	-	-	-	-	1.0	1.0	1.0	1.0
Lower looper	a1.1.1	a1.1.1	a1.1.1	a1.1.2	a1.1.2	a,c1.2 d,e1.2´	a1.1.3	a1.1.3	a1.1.3
Roofing thread	-	Z1	Z,Y1.1.3	Z,Y1.3.1	Z1.1	$Z^{(1)}$1.1.2	$Z^{(1)}$1.1.2	Z,Y1.3.2	$Z^{(2)}$1.1.2

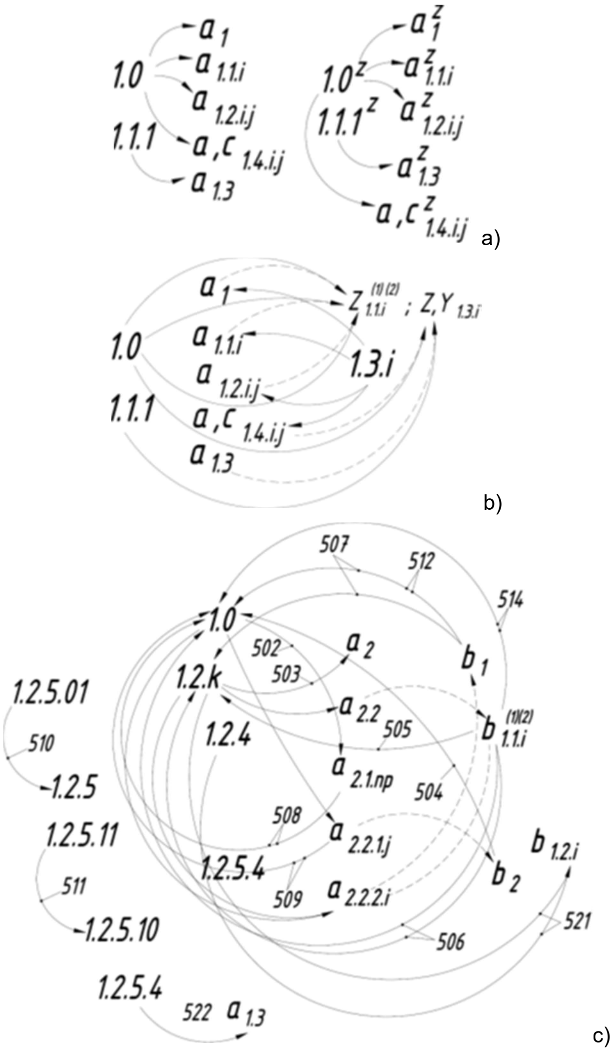


Figure 7 Graph-generator of chain stitches: a) 400 class; b) 600 class, c) 500 class

To determine the length of the stitch and the graphical representation, it is proposed to rearrange the elements of the stitch in the form of a spatial - "3D graph", its base elements and structure are presented in Figure 8. Vertices *11, 12, 13…* and *a1, a2, a3…* reflect the place of needle punctures at the distance of the stitch length *t*, above and below the materials; *11, 21* corresponds to the row spacing between two adjacent needles (*h*), m is the thickness of the materials (depending on the type of stitch may differ and depends on the trajectory of the needle during puncture), *l1,2* - lengths that determine the position of weave threads on the edges of materials and are determined by the structure of the stitch.

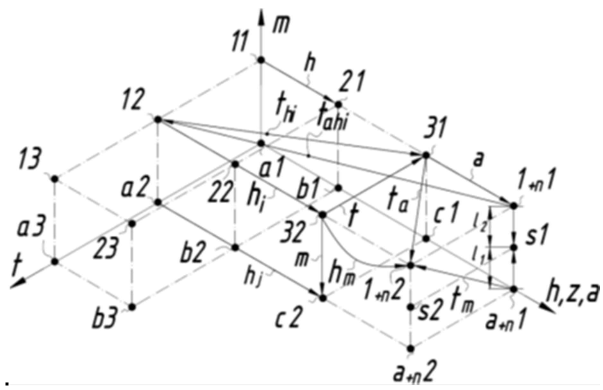


Figure 8 Base of vertices and edges of the "3D-graph" stitch

The "3D subgraphs" of each stitch element in the Table 5 show the sequence of connecting vertices (base points) with edges (elementary sections of the stitch). The length of the "3D subgraph" of the route corresponds to the cost of each thread to form a stitch element, which can be used to automatically determine the length of the stitch thread, as well as to determine the tension of threads when stretching materials, or predict the conditions of stitch tightening.

The lengths of the edges of the "3D graph" (elementary sections of the stitch elements) are determined by the expressions:

$$m' = \frac{m}{\cos\alpha}$$

$$h_i = h \cdot i\ ,\ \ h_j = h \cdot j\ ,\ \ h_{ia} = h \cdot i + a$$

$$t_{hi} = \sqrt{t^2 + (h \cdot i)^2}\ ,\ \ t_{hj} = \sqrt{t^2 + (h \cdot j)^2}$$

$$t_{hia} = \sqrt{t^2 + (h \cdot i + a)^2}$$

$$t_a = \sqrt{t^2 + a^2}\ ,\ \ t_m = \sqrt{t^2 + m^2}\ ,\ \ t_z = \sqrt{t^2 + z^2}$$

$$i = 0, 1, 2, 3 \ldots n\ ,\ \ j = 0, 1, 2, 3 \ldots p$$

where: m - is the thickness of the materials [mm]; m' - the thickness of the materials is equal to the stroke of the needle in the material at an angle (α) in overlocker machines when performing stitches of class 500 [mm]; h_m - is the thickness of the material when holding the loop of the thread of secret sewing machines with an arcuate needle when making stitches of type 103, 105; t - stitch length [mm]; z - is the width of the zigzag [mm]; α is the angle of the needle in the overlocker machines [°]; h - is the length of the broach (distance) between the rows of two adjacent needle threads; h_i, h_j - the length of the broach (branch) of the loops of the threads between the *i-th, j-x* needle rows, respectively, which cover the branches of the loop of the needle thread (main element 1.0) and which are covered by the vertices of their loops [mm]; n - is the number of *i-x, j-x* needle rows (*h = 0, 1, 2 i. i = 0* we have one needle row); a - width of the edging edge of the materials (distance from the edge of the materials to the near needle) [mm]; l_1, l_2 - position of weave loops of threads on the edge of the material (determined by the type of stitch) [mm]; h_{ia} - broach between the *i-th* row and the edge of the materials; t_{hi}, t_{hj}, t_z - is the diagonal broach of the loop branch, respectively, between the *i-th, j-th* rows of needle punctures along the stitch length t; t_a - is the diagonal extension of the loop branch from the edge of the material to the near needle.

Table 5 Routes of 3D graphs of stitch elements

№ p/p	Code of element	The structural formula of the stitch element	Modifier
		Routes of elements of linear stitches	
1	1.0	$11(m)a1(m)11(t)12$	-
2	1.1	$11(m)a1(t)a2(t)a1(m)11(t)12$	t
3	1.1.1.	$11(m)a1(t')a2(t')a1(m)11(t)12$	$t' \approx 0.5t$
4	1.1.2	$11(m)a1(t_h)b2(t_h)a1(m)11(t)12$	$t_h \approx 0.5h$
5	1.1.3	$11(m)a1(t)a2(m)12(t)13(t)12(m)a2(t)a1(m)11(2t)13$	m, t
6	1.1.4	$12(m)a2(t)a1(m)11(2t)13(2t)11(m)a1(t)a2(m)12(t)13$	m, t
7	1.2	$11(m)a1(h)b1(h)a1(m)11(t)12$	h
8	1.2.k	$11(m)a1(h_i)b1(m_k)s1(m_k)b1(h_i)a1(m)11(t)12$	m_k =0; 0,5m; k=3
9	1.2.4	$11(m)a1(h)b1(t_m)22(t_m)b1(h)a1(m)11(t)12$	h=a; t
10	1.2.5	$11(m)a1(h)b1(m)21(t_h)12(t_h)21(m)b1(h)a1(m)11(t)12$	h=a; t, h
11	1.2.5.i.j	$11(m)\ a1(h_{j+1})a_{+j+1}1(m)1_{+j+1}1(t_{hi})1_{j-i+1}2(h_i)1_{+j+1}2(t_{hj-i+1})1_{+j+1}1(m)\ a_{+j+1}1(h_{j+1})a1(m)11(t)22$	h; i=0,1, 2…n; j=0,1,2...p
12	1.2.5.1	$11(h_m)21(t_h)12(t_h)21(t_m)11(t)12$	
13	1.2.5.2	$21(t_h)12(t_m)22(t_m)12(t_h)21(t)22(t_m)32\ (t_h)23(t_h)\ 32(t_m)22(t)23$	h; t; t_m;
14	1.2.5.3	$21(l_1)s1(l_1)21(h)11(m)a1(h)b1(l_2)s1(t)s2(t)s1(l_2)b1(h)a1(m)11(t_h)22$	$l_1=l_2$=0,5m; t; h
15	1.2.5.4	$11(m)a1(m)11(h)21(m)b1(t_{hi})a2(t_{hi})b1(m)21(t_{hj})12$	m; t; h
16	1.3.	$21(m)b1(m)21(t_h)12(h)22$	h
17	1.3.i	$1_{+i}1(m)a_{+i}1(m)1_{+i}1(t_{hi})12(h_i)\ 1_{+i}2$	i=0,1,2…n
18	a1	$a1(t)a2(t)a1(t)a2$	
19	a1.1.i	$a_{+i}1(h_i)a1(t)a2(t)a1(t_h)a_{+1}2(t)a_{+1}1(t_h)\ a_{+2}2(t)\ a_{+2}1(t_h)\ldots\ a_{+i}2(t)\ a_{+i}1(t)a_{+i}2$	i=0,1,2...n
20	a1.2	$a1(t)a2(h)b2(t_h)a1(t)a2$	h
21	a1.2.i.j	$a_{+j}1(h_j)a1(t)a2(h_i)a_{+i}2(t_{hi})a1(h_j)a_{+j}1(t)a_{+j}2$	h; i=0,1, 2…n; j=0,1,2...p
22	a1.3	$a1(t)a2(t')s(t')a1$	$t' \approx 0.5t$
23	a1.4	$a1(t_h)b2(t_h)a1(t)a2$	h
24	a1.4.i.j	$a1(h_j)a_{+j}1(t_{hi})a_{+i+j}2(h_i)a_{+j}2(t_{hi})a_{+j}1(h_j)a1(t)a2$	h; i=0,1, 2…n; j=0,1,2...p
25	b1≡Z1	$b1(t_h)a2(t_h)b1$	h
26	$b,Z^{(1)(2)}1.1.i$	$a_{+i}1(t_{hi})a2(h_i)\ a_{+i}2$	i=0,1,2…n
27	b1.2	$b1(t_h)a2(t_h)b1(t)b2$	t
28	b1.2.i	$a_{+i}1(t_{hi})a2(t_h)b1(t)b2k1(t_{hj})a2(h_i)k1(t)k2$	j=1,2,3…p
29	$Z,Y^{(1)}1.3.i$	$a_{+i}1(t_{hi})a2(t_{hi})\ a_{+i}3$	i=0,1,2…n; t_2=2t
30	a2≡b2	$s1(l2)b1(t_h)a2(t_h)\ b1(l2)s1(t)s2$	l2=0.5m
31	a2.1	$a1(h)b1(m)21(t_h)12(t_h)21(m)b1(h)a1(t)a2$	h=a
32	a2.1.i.j	$a1(h_{j+1})a_{+j+1}1(m)1_{+j+1}1(t_{hi})1_{+j-i+1}2(h_i)1_{+j+1}2(t_{hj-i+1})1_{+j+1}1(m)\ a_{+j+1}1(h_{j+1})a1(t)a2$	h; i=0,1, 2…n; j=0,1,2...p
33	a2.2	$a1(m)11(m)a1(t)a2$	m
34	a2.2.1	$a1(h)b1(l1)s1(l1)b1(h)a1(t)a2$	h=a, l1=0.5m
35	a2.2.1.j	$a1(h_{j+1})\ a_{+j+1}1(l1)s1(l1)\ a_{+j+1}1(h_{j+1})a1(t)a2$	l1=0.5m, j=1,2,3…p
36	a2.2.2	$a1(h)b1(m)21(t)22(m)b2(t_h)a1(t)a2$	h=a; t
37	a2.2.2.j	$a1(h_{j+1})a_{+j+1}1(m)1_{+j+1}1(t)1_{+j+1}2(h_{j+1})a1(t)a2$	h; j=0,1,2...p
		Routes of elements of zigzag stitches	
38	1.0^z	$11(m)a1(m)11(t_z)22$	z; $t_z \equiv t_h$
39	1.1^z	$11(m)a1(t_z)b2(t_z)a1(m)11(t_z)22$	z
40	$1.1.1^z$	$11(m)a1(t'_z)b2(t'_z)a1(m)11(t_z)22$	z; $t' \approx 0.5t$
41	$1.1.3^z$	$11(m)a1(t_z)b2(m)22(t_z)33(t_z)22(m)b2(t_z)a1(m)11(2t_z)33$	z
42	$1.1.4^z$	$22(m)b2(t_z)a1(m)11(2t_z)33(2t_z)11(m)a1(t_z)b2(m)22(t_z)33$	z
38	1.0^z	$11(m)a1(m)11(t_z)22$	z; $t_z \equiv t_h$
43	$a1^z$	$a1(t)b2(t)a1(t)b2$	z
44	$a1.1.i^z$	$a_{+i}1(h_i)a1(t_z)a_{+1}2(t_z)a1(t_{z+1})a_{+2}2(t_z)a_{+1}1(t_{z+1})\ a_{+3}2(t_h)\ a_{+2}1\ldots(t_{z+1})a_{+i+1}2(t_z)\ a_{+i}1(t_z)a_{+i}2$	z; i=0,1,2...n
45	$a1.2.i.j^z$	$a_{+j}1(h_j)a1(t_z)a_{+j-j}1(h_i)a_{+i+1}2(t_{hi+1})a1(h_j)a_{+j}1(t_z)a_{+j}2$	z; i=0,1, 2…n;
46	$a1.3^z$	$a1(t_z)b2(t_z')s(t_z')a2$	$t_z' \approx 0.5\ t_z$

A certain combination of stitch elements in turn forms the stitch structure, and the total length of the contours of the elements reflects the number of specific threads that are earned in one stitch, and can be determined geometrically and adjusted by factors that take into account the properties of materials and threads. It should be noted that the actual length of the thread in the stitch depends on certain factors (deformation of materials, thread stiffness, twisting, etc.), geometries of thread guides, laws of motion of thread feeders, coordinated interaction of loop-forming bodies, etc.

Also, the "3D graph" of each stitch element (Table 5) can be represented by the incidence matrix Gi [22] in which the coordinate axis (X, Y, Z) are represented by edges along the ordinates (*t, h, m*), which allows not only to show the incidence of vertices, and the direction of the contour of a particular thread in the stitch element, which can be used to determine the flow of threads in the stitch, the force of their tension, etc.

$$G_i = (V, X), \quad V = \{v_1, \dots v_n\}, \quad X = \{x_1, \dots x_k\} \tag{2}$$

$$G_i = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1k} \\ a_{21} & a_{22} & \cdots & a_{2k} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nk} \end{pmatrix}$$

$$a_{ij} = \begin{cases} 1, \mathit{if}\ x_j\ \text{then iз}\ v_i \\ -1, \mathit{if}\ x_j\ \text{then in}\ v_i \\ 0, \mathit{if}\ x_j \text{not incidental}\ v_i \end{cases}$$

where: G_i - incident matrix of the element of the *i-th* stitch, *V* - vertices of the graph (*11, 12, 1.3 … n1, n2, n3… a1, a2, … s1, s2… n+1, a+p* - depending on the structure of the stitch element (Figure 7)); *X* - the edges of the graph (*m, m´, t, l, h*).

A full description of the stitch structure by the incidence matrix *G* "3D graph" can be found by combining the incidence matrices of 3D/2D subgraphs, which express certain elements of the stitch:

$$G = G_1 \dots \cup G_n \cup G_A \dots \cup G_n \cup G_B \cup G_Z \cup G_Y \tag{3}$$

where: $G_1 \dots G_n$ - incident matrix 3D subgraph of the *i-th* needle thread; $G_A \dots G_n$ - incidental matrix 3D/2D subgraph of the *i-th* element of the lower loop thread; G_B - incident matrix 3D/2D subgraph of the *i-th* element of the thread of the upper loop; G_Z, G_Y - incident matrix of 2D subgraph of the *i-th* element of threads *Z* and *Y* of the top cover spreader.

The general incident matrix in accordance with the vertices *V* and edges *N* will look like:

$$G = \begin{pmatrix} & 11 & 12 & \dots & n1 & n2 & a1 & a2 & \dots & n1 & n2 & \dots & s1 & s2 & \dots \\ t & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ m, m', m'' & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ h, z, a & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ t_{h_i}, t_{h_j}, t_a & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ l_1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ l_2 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix} \tag{4}$$

Consider similar structures of stitches of type 402 and 403 (Figures. 9 and 10), which differ only in the presence in the stitch of type 403 of the third needle thread and loop thread - *a1.1.2*.

Then the incidence matrices (correct all terms) for stitch elements of type 402 and 403 using (2) for the needle thread of the loop we get:

$$G^{402}_{1;2} = \begin{pmatrix} & 11 & 12 & 21 & 22 & a1 & a2 & b1 & b2 \\ t & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ m & 1;-1 & 1;-1 & 1;-1 & 1;-1 & -1;1 & -1;1 & -1;1 & -1;1 \end{pmatrix}$$

$$G^{402}_{a1.1.2} = \begin{pmatrix} & a1 & a2 & b1 & b2 \\ t & 1 & -1 & 1 & -1 \\ h & -1,1 & 1 & 1,-1 & -1 \\ t_{h,i=1} & -1 & 0 & 0 & 1 \end{pmatrix}$$

$$G^{403}_{1;2;3} = \begin{pmatrix} & 11 & 12 & 21 & 22 & 31 & 32 & a1 & a2 & b1 & b2 & c1 & c2 \\ t & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ m & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 \end{pmatrix}$$

$$G^{403}_{a1.1.2} = \begin{pmatrix} & a1 & a2 & b1 & b2 & c1 & c2 \\ t & 1 & -1 & 0 & 0 & 1 & -1 \\ h & -1,1 & 1 & 1,-1 & -1,1 & 1,-1 & -1 \\ t_{h,i=2} & -1 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

By expression (3) we obtain the intensity matrices (4) for stitches of type 402 and 403:

$$G^{402} = G^{402}_{1;2} \cup G^{402}_{a1.1.2}, \qquad G^{403} = G^{403}_{1;2;3} \cup G^{403}_{a1.1.2}$$

$$G^{402} = \begin{pmatrix} & 11 & 12 & 21 & 22 & a1 & a2 & b1 & b2 \\ t & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ m & 1;-1 & 1;-1 & 1;-1 & 1;-1 & -1;1 & -1;1 & -1;1 & -1;1 \\ h & 0 & 0 & 0 & 0 & -1,1 & 1 & 1,-1 & -1 \\ t_{h,i=1} & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 \end{pmatrix}$$

$$G^{403} = \begin{pmatrix} & 11 & 12 & 21 & 22 & 13 & 32 & a1 & a2 & b1 & b2 & c1 & c2 \\ t & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 1 & -1 \\ m & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 \\ h & 0 & 0 & 0 & 0 & 0 & 0 & -1;1 & 1 & 1;-1 & -1;1 & 1;-1 & -1 \\ t_{h,i=2} & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

For analogy of the intensity matrix for stitches of type 504 and 606 (Figures 11 and 12).

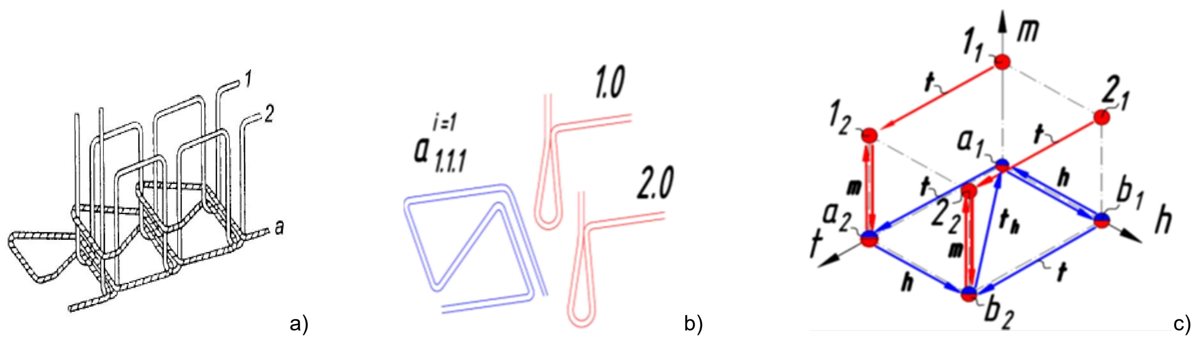


Figure 9 Topological analysis of stitch type 402: a) stitch structure; b) stitch elements; c) "3D-graph" stitch

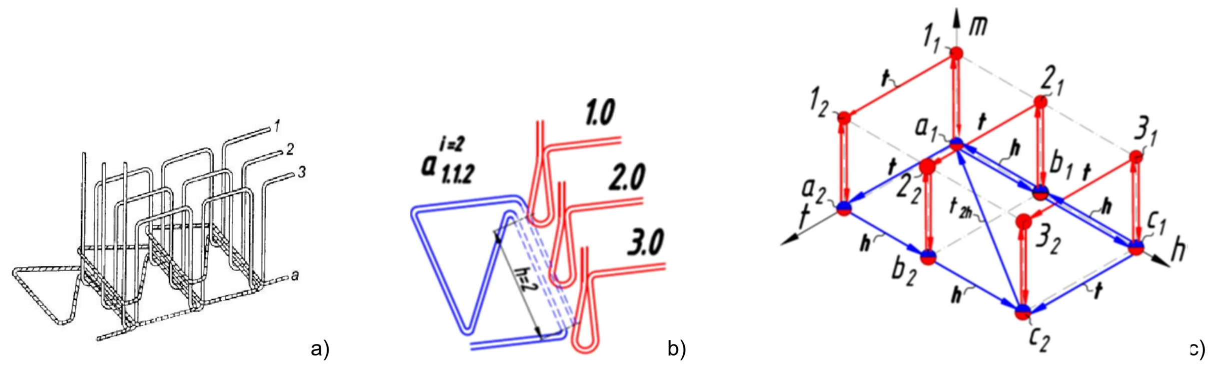


Figure 10 Topological analysis of stitch type 403: a) stitch structure, b) stitch elements, c) "3D graph" stitch

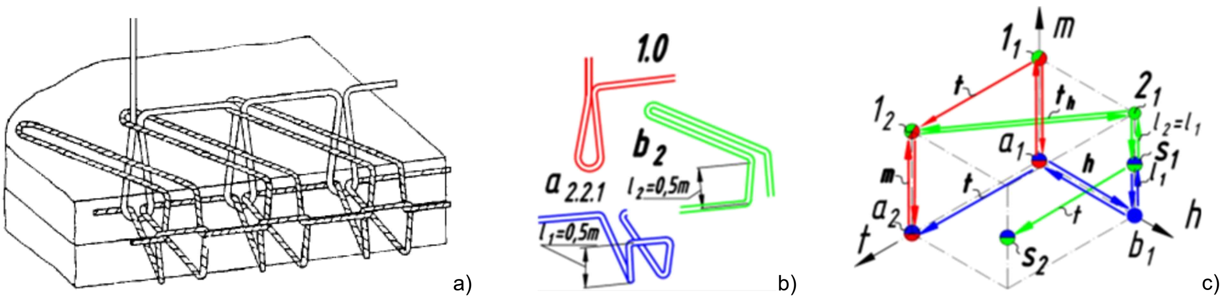


Figure 11 Topological analysis of the stitch type 504: a) stitch structure, b) stitch elements, c) "3D - graph" stitch

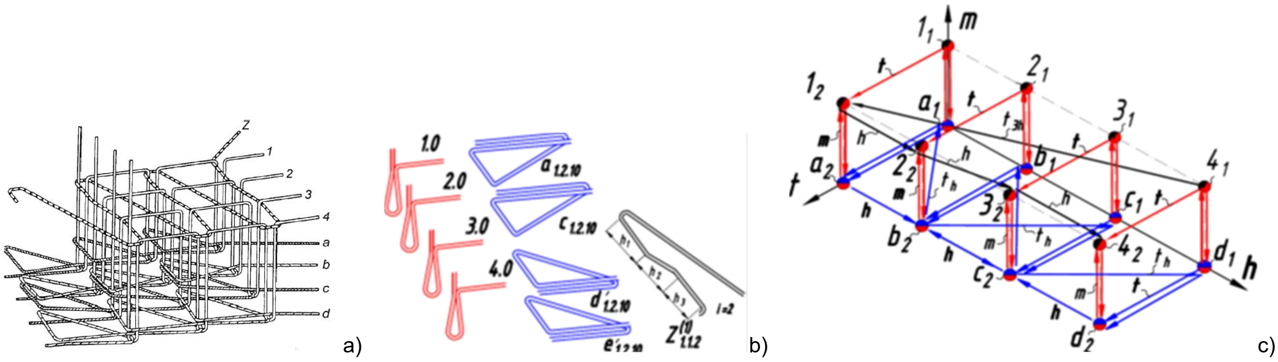


Figure 12 Topological analysis of the stitch type 606: a) stitch structure; b) stitch elements; c) "3D - graph" stitch

Then the intensity matrices for stitch elements of type 504 and 606, similarly applying (2) to the needle thread of loops and cover thread we get:

$$G^{504}_{1}=\begin{pmatrix} & 11 & 12 & a1 & a2 \\ t & 1 & -1 & 0 & 0 \\ m & 1;-1 & 1;-1 & -1;1 & -1;1 \end{pmatrix} \qquad G^{504}_{b_2}=\begin{pmatrix} & s1 & 21 & 12 & s2 \\ l2 & 1;-1 & -1;1 & 0 & 0 \\ t_{h,j=1} & 0 & 1;-1 & -1,1 & 0 \\ t & 1 & 0 & 0 & -1 \end{pmatrix} \qquad G^{504}_{a_{2.2.1}}=\begin{pmatrix} & a1 & b1 & s1 & a2 \\ a=h & 1;-1 & -1;1 & 0 & 0 \\ l_1 & 0 & 1;-1 & -1,1 & 0 \\ t & 1 & 0 & 0 & -1 \end{pmatrix}$$

$$G^{606}_{1;2;3;4}=\begin{pmatrix} & 11 & 12 & 21 & 22 & 31 & 32 & 41 & 42 & a1 & a2 & b1 & b2 & c1 & c2 & d1 & d2 \\ t & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ m & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & 1;-1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 & -1;1 \end{pmatrix}$$

$$G^{606}_{\substack{a_{1.2.10}\\ c_{1.2.10}\\ d'_{1.2.10}\\ e'_{1.2.10}}}=\begin{pmatrix} & 11 & 12 & 21 & 22 & 31 & 32 & 41 & 42 & a1 & a2 & b1 & b2 & c1 & c2 & d1 & d2 \\ t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & -2 & 2 & -2 & 2 & -2 & 2 & -2 \\ m & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ h & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -2;1 & 0 & -2;1 & 0 & 1 \\ t_{h,i=1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & -1 & 2 & -1 & 2 & -1 & 0 \end{pmatrix}$$

$$G^{606}_{Z^{(1)}_{1.1.2}}=\begin{pmatrix} & 11 & 12 & 21 & 22 & 31 & 32 & 41 & 42 \\ h & 0 & 1 & 0 & 1;-1 & 0 & 1;-1 & 0 & -1 \\ t_{h,i=3} & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Then the intensity matrices for stitches of types 504 and 606:

$$G^{504}=G^{504}_{1}\cup G^{504}_{a2.2.1} \qquad G^{606}=G^{606}_{1;2;3;4}\cup G^{606}_{\substack{a_{1.2.10}\\ c_{1.2.10}\\ d'_{1.2.10}\\ e'_{1.2.10}}}\cup G^{606}_{Z^{(1)}_{1.1.2}}$$

$$G^{504}=\begin{pmatrix} & 11 & 12 & 21 & 22 & a1 & a2 & b1 & b2 & s1 & s2 \\ t & 1 & -1 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 \\ m & 0 & 1;-1 & 0 & 0 & 0 & -1;1 & 0 & 0 & 0 & 0 \\ a & 0 & 0 & 0 & 0 & 1;-1 & 0 & -1;1 & 0\ 0 & 0 & 0 \\ t_{h,i=1} & 0 & -1;1 & 1;-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ l_1 & 0 & 0 & 0 & 0 & 0 & 0 & 1;-1 & 0 & -1;1 & 0 \\ l_2 & 0 & 0 & -1;1 & 0 & 0 & 0 & 0 & 0 & 1;-1 & 0 \end{pmatrix}$$

$$G^{606}=\begin{pmatrix} & 11 & 12 & 21 & 22 & 31 & 32 & 41 & 42 & a1 & a2 & b1 & b2 & c1 & c2 & d1 & d2 \\ t & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 2 & -2 & 2 & -2 & 2 & -2 & 2 & -2 \\ m & 0 & 1;-1 & 0 & 1;-1 & 0 & 1;-1 & 0 & 1;-1 & 0 & -1;1 & 0 & -1;1 & 0 & -1;1 & 0 & -1;1 \\ h & 0 & 1 & 0 & -1;1 & 0 & -1;1 & 0 & -1 & 0 & 1 & 0 & -2;1 & 0 & -2;1 & 0 & -1 \\ t_{h,i=1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & -1 & 2 & -1 & 2 & -1 & 0 \\ t_{h,i=3} & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

4 CONCLUSIONS

The performed topological analysis of chain stitch structures of classes 100, 400, 500, 600, 800 provides an opportunity to determine the hierarchical heredity of stitch elements origin and their formation, which can be used to establish patterns of stitch structure formation, its classification, etc.

The obtained morphological matrices of stitch structure allow to reveal the affiliation of the application of certain elements to a particular stitch, which can be used to build a relational database of chain stitches, system analysis of stitches and additions and extensions DSTU ISO 4915: 2015.

The obtained combinations of possible relationships of stitch elements allow to form a generator of possible stitch structures, which allows the formation of new stitch structures of different classes and properties.

The obtained "3D-graphs" and structural formulas of stitch types of classes 100, 400-600 and 800 allow to determine the length of each thread in the stitch, and, accordingly, the cost of threads per stitch. In addition, the results can be used to graphically interpret a particular stitch structure using computer technology, as well as to model dynamic parameters such as stitch and yarn deformation, yarn strength, stitch formation conditions, and so on.

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