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Spatial Model of the Structure of Warp – Knitted 3D Distance Fabrics

Abstract
This article presents a geometrical model of three – and five – layer 3D distance knitted fabric which characterises the structural features of the fabric in a spatial Cartesian xyz system. New notions (technical terms) of 'spatial a – jours' and 'spatial reliefs' are introduced. Spatial a – jours are channelled layer structures inside knitted fabrics, whereas spatial reliefs are characterised by a different structure of the internal, as well as external layers, which are the result of a different thickness of the fabric layer's segements. A hybrid model was developed of the graphical description of a 3D distance knitted fabric. This model includes a description of the thread continuum in the fabric stitch using of the 2D system. Whereas considered a solid, it presents the spatial architecture of the knitted fabric. The model composition was verified by an analysis of the real structures of twenty stitch variants.

Key words: *knitted distance fabrics, 3D structures, spatial a – jours, spatial reliefs, spatial model, graphical model.*

Introduction

3D distance warp – knitted fabrics have been known for many years and found a broad range of applications in the footwear and medical product industries for the production of mattresses as different kinds of protectors, as well as in different textile products, among others [1-4].

The knitted fabrics discussed in this article are manufactured with the use of warp knitting machines equipped with two needle combs (*P* and *T* in ***Figure 1***), which are positioned parallel to each other [5]. The distance *x* between both needle combs can be equal to 1.5-6.6 mm and determines the thickness g_i of the knitted fabric, manufactured in such a way that $g_i \approx x$. Six guide bars, two per layer, are used on two – needle comb warp knitting machines.

In the literature connected with such knitted fabrics, different structures of 3D distance knitted fabrics are described [6], but no generalised model can be found which would describe their structure. In order to describe the stitches, methods similar to the description of plain and moss stitches of "flat" knitted fabrics are used, which do not give any information of the spatial structure of the knitted fabric. The authors based their research on schematic drawings of the stitch description, in which dots and crosses are used, relating to the front and back needle combs. It is difficult to draw conclusions from the stitch description about the spatial structure of 3D distance knitted fabrics. A method was proposed consisting in the elaboration of a graphical sheet used for the designing of the structure and stitches of 3D distance warp – knitted fabrics. Such a sheet is completed by cross – sections of the product along the wales and courses [7]. The literature figures demonstrate the spatial structure of stitch fragments of knitted fabrics manufactured in the shape of so – called "sleeves" used for illustrating final products. Such a description concerns only structures presented in academic text books but are not used in the classical designing of knitted fabrics [5].

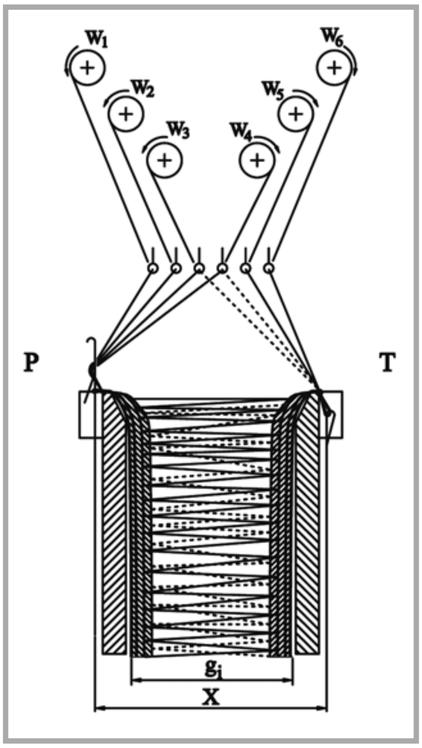

Figure 1. *Technology of 3D distance warp-knitted fabrics; P, T – needle combs, x – distance between needle combs,* g_i *– knitted fabric thickness,* $w_1, w_2, ..., w_6$ *– yarn windings.*

3D distance knitted fabrics are complex structures considering the different construction of the external layers as well as the internal layer, which up to the present has not been taken into consideration using the methods describing the structure of this group of knitted fabrics. The statements mentioned above, which consider 3D distance warp – knitted fabric as a 2D product, inspired the authors of this article to elaborate a model description of the knitted fabric structure in a spatial system, and formulate assumptions for a hybrid graphical description model of the stitches used. The aim of the model presented is the possibility of determinating the structural parameters of distance warp – knitted fabrics as a spatial solid. These parameters and the relations between them will be used in designing product properties, including physical and mechanical properties.

Geometrical model of a 3D distance warp – knitted fabric

The most often used structures of 3D distance warp – knitted fabrics are build from three layers: two external layers el_1 and el_2 and an internal layer *il* ***(Figure 2)***. The distance between the external layers is determined by the thickness g_i of the knitted fabric, which is significantly greater than the thickness of plain (flat) knitted fabrics manufactured on single – comb classical warp knitting machines, which means that $g_i \rangle\rangle g_{l-p}$. The external layers are formed by independent plain stitches and loops of moss stitches. Links (connectors) are positioned between these loops and form the internal layer. In the case of more complex structures, weft stitches are used in the internal layers. The structure of the external layers el_1 and el_2 can be similar or different.

Among different distance knitted fabrics, five – layer knitted fabrics can also be distinguished ***(Figure 3)*** [8]. In this case we have two internal layers which can be characterised by different thicknesses, variable thread density in the layers, as well as by the spatial structure of the stitch. Differences exist between the structure of the external layer el_1 and el_2 and the middle layer *ml*. The external layers are build from plain stitches and loops of moss stitches, similar to three – layer knitted fabrics; but the middle layer *ml* is formed by thread connections of the internal layers il_1 and il_2 (in this layer stitch loops do not exist).

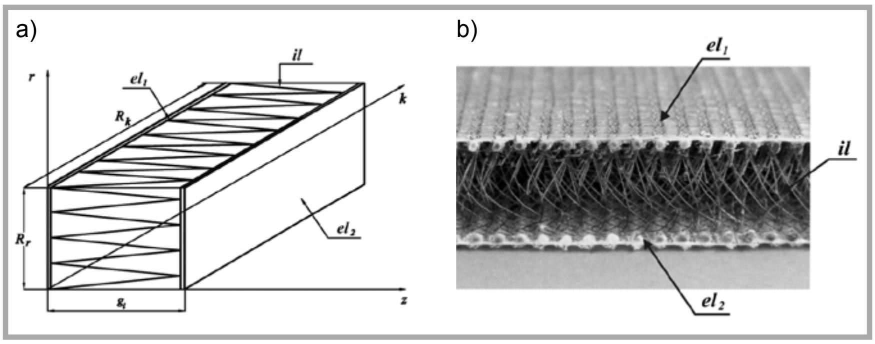

Figure 2. *Three-layer 3D distance knitted fabric; a) geometrical model, b) real view; el_1, el_2 – external layers, il – internal layer, R_r – course report in direction of r-axis, R_k -wale. report in direction of k-axis.*

In this article the model form of three – layer and five – layer knitted fabrics is presented in a spatial Cartesian *xyz* system.

The external layers of the product, which are based on the structure of plain wale stitches, can be composed of the following knitted structure: multi guide bar a – jour knitted fabrics, smooth knitted fabrics, weft knitted fabrics, plated knitted fabrics, two needle comb knitted fabrics, as well as multi – colour and structural jacquard knitted fabrics.

In order to manufacture the external layers of distance knitted fabrics, synthetic yarns are most often used, but yarns from natural fibres can also be applied. In the case of technical products, the internal layer is built from polyamide or polyester monofilaments whose linear density, in the majority of cases, is within the range of 22 dtex to 87 dtex [9].

3D distance knitted fabrics have an equal structure of the loop geometry for both external layers, which means that the height *B* of a course of loops is equal to the width *A* of the wale of loops. However, it is possible to create a structure of knitted fabric differentiated by the geometry of fabric courses, for example an 'undulating' external plane el_1 as opposed to a 'flat" external plane el_2.

Spatial a – jours

A new notion (technical term) of a – jour spatial knitted fabrics is introduced in this article (instead of a – jour, the term 'open work' is also used). This term refers to classical flat wale a – jour knitted fabrics (warp – knitted fabrics of open – work design) in which a – jours in the shape of openings are formed by not connecting the loops of two neighbouring wales over the distance of several courses. Analogical spatial a – jour knitted fabrics are structures in which internal spaces not occupied by yarn are the effect of a lack of connections between external layers; such forms are called channels (ducts). As the definition of a a – jour spatial knitted fabric is a new one, it is not presented in Polish and European standards, which describe the system of knit wear stitches.

The following kinds of channels can be formed by an appropriate selection of stitches and the threading of guide bars:

a) longitudinal,
b) transversal,
c) perpendicular to the knitted fabric surface.

Longitudinal (vertical) channels of a – jour knitted fabric are formed as a result of selecting appropriate component stitches of the knitted fabric, which are characterised of a lack of connections for a width determined by the number of wales. The channel height is determined

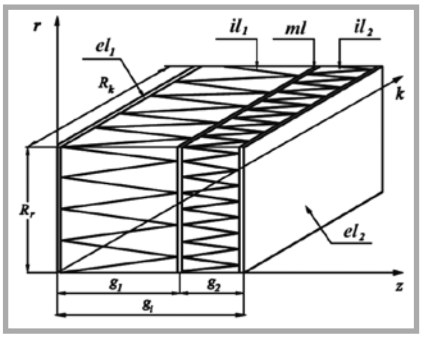

Figure 3. *Geometrical model of a five – layer 3D distance knitted fabric; R_r – course report in direction of r – axis, R_k – wale report in direction of k – axis, el_1, el_2 – external layers, il_1, il_2 – internal layer, ml – middle layer, g_i – knitted fabric thickness, g_1, g_2 – internal component layer thickness.*

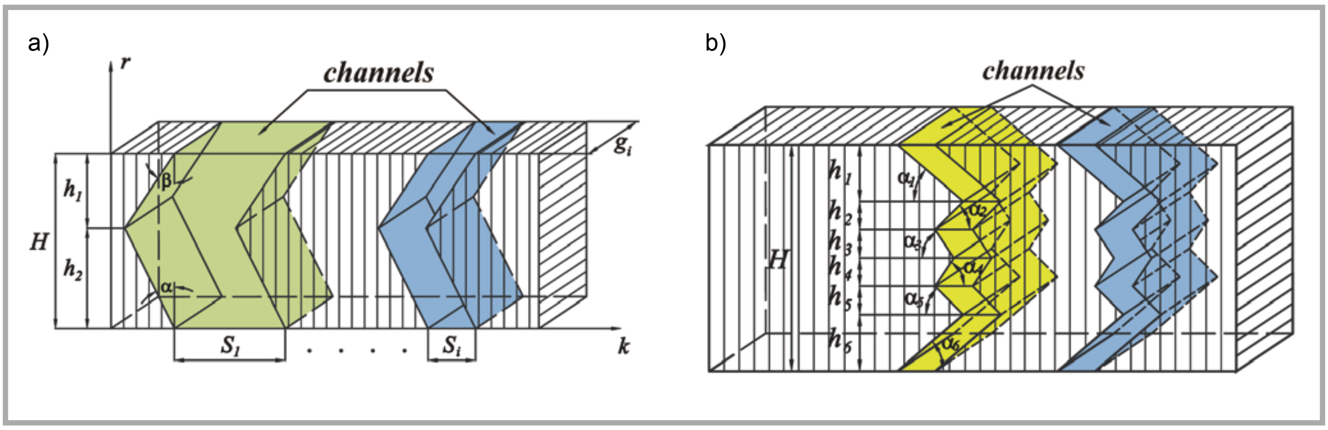

***Figure 4.** Model of a longitudinal channel: a) with different widths, b) with a complex internal surface. H – channel height, h_1, h_2,...h_i, – heights of channel segments, S_1,...S_i – channel widths, α, β – angles of channel plains.*

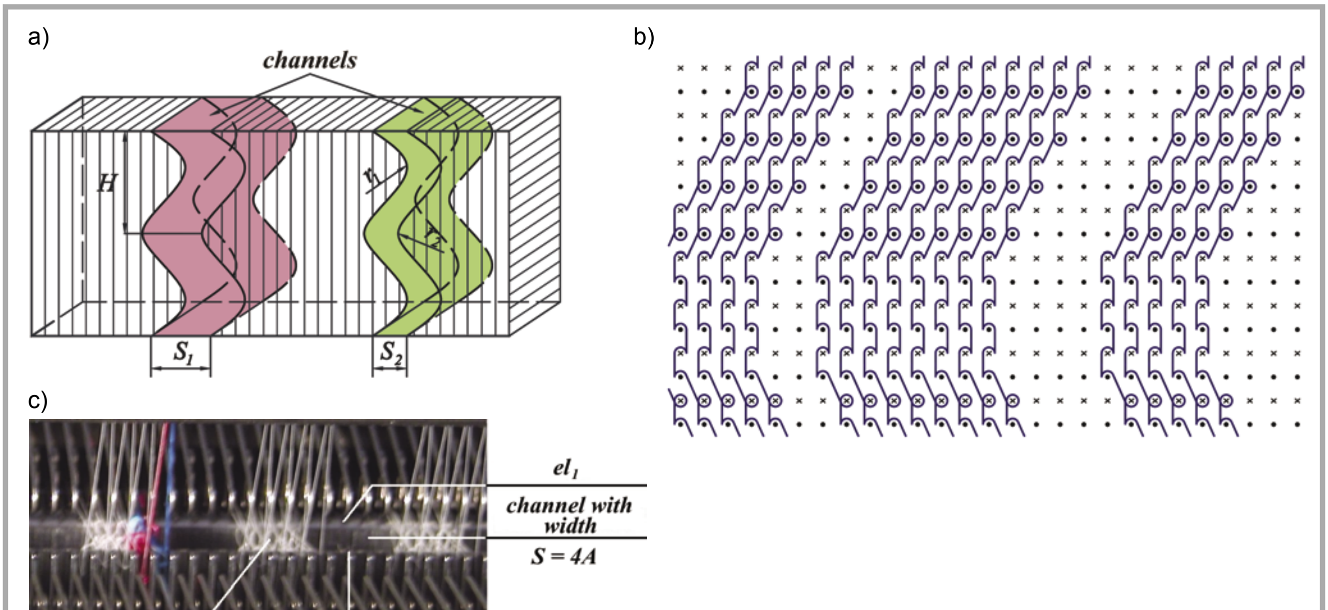

***Figure 5.** An example of a longitudinal channel modelled by curvatures; a) geometrical model, b) an example of the stitch of a knitted fabric's internal layer, c) the way of manufacturing a channel on a warp knitting machine; the notations as in Figure 4.*

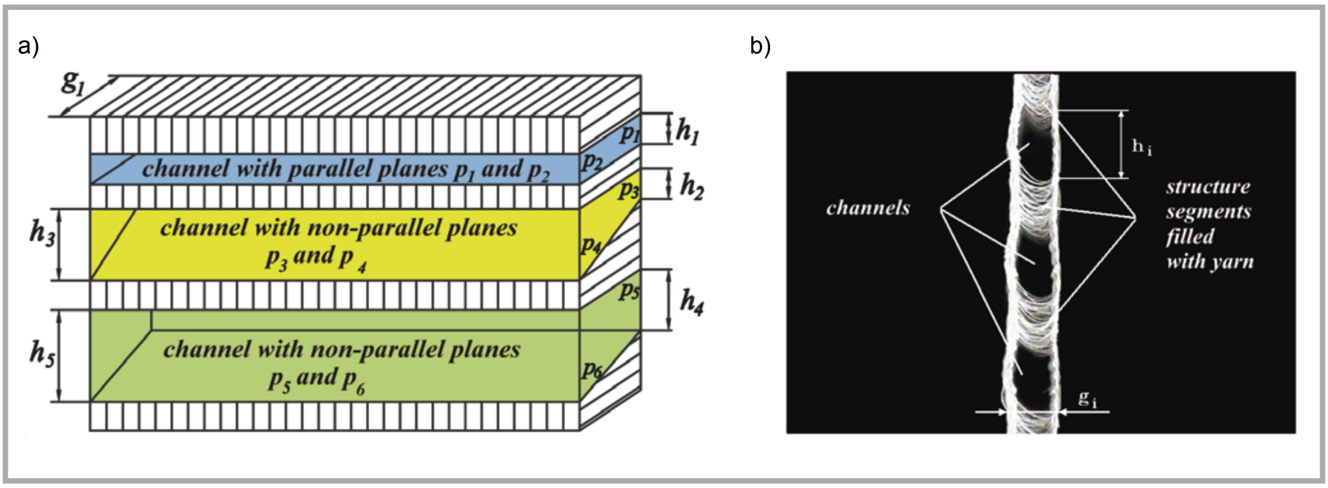

***Figure 6.** Transversal channels; a) geometrical model, b) cross section of the distance knitted fabric; p_1, p_2,...p_6 – channel planes, notations different from the notations in Figure 5.*

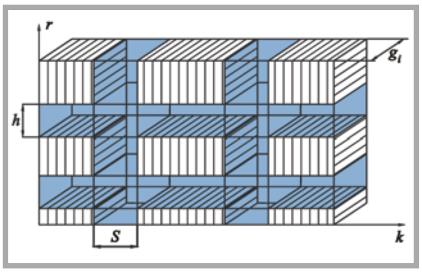

Figure 7. *Geometrical model of a connection of longitudinal and transversal channels; g_i – fabric thickness, h – channel height, S – channel width.*

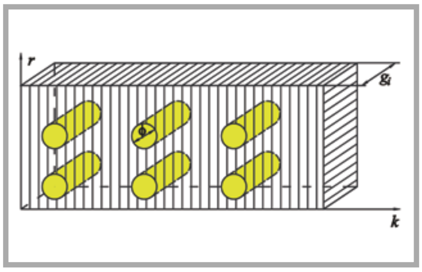

Figure 8. *Knitted fabric with channels of cylindrical shape perpendicular to its external surface; g_i – fabric thickness, Φ – channel diameter.*

by the product $H = n \cdot B$, were n is the number of courses and B the height of the loop courses. The width S of the channel depends on the report of the partial threading of the guide bars, and can be changed if required ***(Figure 4.a)***. Assuming that the width A of a wale of loops is nearly equal to the spacing of needling, and x is the number of unfed guide bars, we can determine the approximate width of the channel $S = x \cdot A$. The depth g of the channel is determined by the knitted fabric thickness g_i ,which depends of the distance x between the needle combs. In the case of the model presented, the total height H of the channel can include several segments of different structure and height h_i, and thus

$$H = \sum_{i=1}^{n} h_i \ ,$$

where n is the total number of segments of the stitch report. The vertical channels form planes of the knitted fabric's external layers; however, these planes have the same thickness as the distance layer. In the simplest channels, they are parallel to the line of wales. In the case of more complex channels, the planes of the internal structure of the knitted fabric are not parallel, and their position is determined by the angles α and β. If the angles are equal to $0°$, then we obtain simple, straight vertical channels. Such parameters as the height and width of the loop A and B, the thickness g_i of the knitted fabric, and the angles α and β determine the volume of a longitudinal channel within the boundaries of the stitch report.

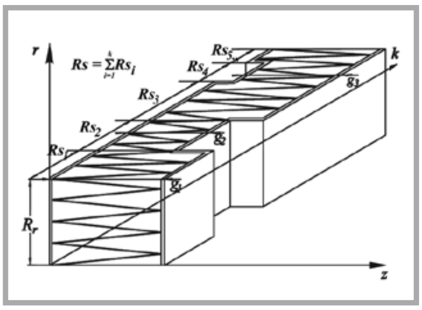

Figure 9. *A spatial geometrical model of a relief distance knitted fabric; Rs_1, Rs_2...Rs_i – segment widths, Rs – sum of the component widths, g_1, g_2, g_3 – segment thicknesses, R_r – course report.*

A longitudinal channel can also have a complex internal surface ***(Figure 4.b)***, in which the total height of the channel report is composed by a row of heights h_i of component segments with different slope angles α_i. Due to such a channel structure, its real length is significantly longer in comparison to that of a simple, straight vertical channel.

The shape of a channel can be also modelled with the use of a curvature with a radius r. With dependence on the channel design, the stitch report can be characterised by different radii of the curvature ***(Figure 5.a)***.

The cross – section of longitudinal channels can take the shape of a rectangle, hexagon or rhombus, which depend on the position of connectors in the internal layer.

Figure 5.c presents the way of forming a vertical channel on a RMDU6 two – comb warp knitting machine. In this case the width of the channels obtained and the filed segments are the same, and equal to $S = 4 \cdot A$.

A transversal channel ***(Figure 6.a)*** is formed as the result of a local lack of threads in the component stitches which form the internal layer. The connectors of the internal layer are also placed in one or both external layers.

In the case of transversal channels, contrary to vertical channels, practically no possibility exists of creating systems of planes with different angels and surfaces modelled with the use of different curvatures. The only possibility which exists is changing the channel height h_i in the system of horizontal parallel plains or non – parallel planes in relation to the horizontal channel.

In spatial a – jour knitted fabrics, the channel of both kinds (longitudinal and transversal) can be mutually connected, forming complex structures of spatial empty solids, unfilled by yarn, of the internal layers ***(Figure 7)***.

The next aspect of the structure of spatial a – jour knitted fabric discussed are channels perpendicular to the external surface of the product.

Due to modifying the component stitches, we can influence the shape of the channels obtained. They can have the shape of a spatial solid – cylinder or of a prism with different areas of the transversal cross – sections. Such channels can be positioned in the interior of a 3D knitted fabric when the external layers are smooth, which gives closed channels in the structure, or can create openings going through the total thickness of the fabric when in the external layers a – jours are formed; in this way we obtain open channels. As regards open channels, a continuity should be provided when creating subsequent loops in the external layers.

Figure 8 presents an example of a knitted fabric structure with cylindrical channels of a diameter Φ, which are perpendicular to the external layer.

Spatial reliefs

The next new notion concerning the structure of 3D distance warp – knitted fabrics are spatial reliefs. Such reliefs can be defined as external structures surrounded by a non – regular system of planes of different width, which as a result of their structures form segments with various thicknesses. In certain cases, the segments have a thickness of one of the external layers. ***Figure 9*** presents a geometrical spatial model of a relief distance knitted fabric. The structure of such a knitted fabric is connected with a new concept of warp knitting machine design, which would have the possibility of changing the distance between needles, not only across the total length of the machine, but also in the range determined by the lead segments with needles.

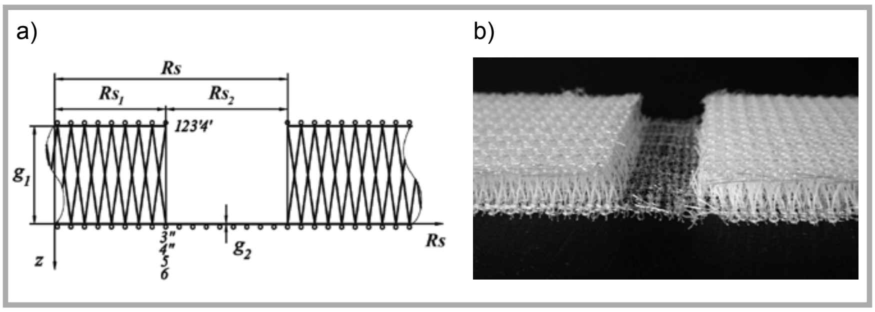

Figure 10. *Relief distance knitted fabric with a partial lack of one of the external layers and the internal layer; a) schematic drawing, b) cross section of the knitted fabric; the notations as in Figure 7.*

The spatial model in ***Figure 9*** presents a relief distance knitted fabric composed of k segments with different widths Rs_i, which as a result give the total width *Rs* in the spatial report of the fabric. The segment width can be obtained by selecting the repeatability of the number of lead segments with needles across the width of the machine. With dependence on the mutual positioning of the lead segments on the left and the right side of the product, we can model the thickness gi of the particular segments Rs_i.

A special case amongst the group of products discussed is a relief knitted fabric with a partial lack of one of the external layers and the internal layer ***(Figure 10)***.

In the example presented, for the width Rs_2 of the report, a lack of the threads which compose one of the external layers and the internal layer can be observed. In this case the knitted fabric is built only from threads which compose the opposite external layer of thickness g_2.

Characteristic features of the structure of the distance internal layer

In the internal layers of knitted fabrics, connectors (links) are most often used, which connect the opposite loops of the external structures of the fabric. By appropriate selection of the stitch, we can form the arrangement of these connectors, which is decisive for the structure and properties of the knitted fabric. ***Figure 11*** presents an example of a possible configuration variant of the internal layer connectors.

The connectors can be formed in the plane *r-k* of the knitted fabric cross section, along the courses, by changing the angle *α*; this can also be done in the plane *r-z*, which lies along the wales, by changing the angle *β*. In a special, particular case the spatial configuration of a connector can also be changed by influencing the knitted fabric thickness g_i, which is modelled by the change in the distance *x* between the external layers of the knitted fabric. For a knitted fabric with the same dimensions of the loops (*A* and *B*), the angles at which the monofilaments are arranged decrease with an increase in thickness g_i.

The value of the angle *α* depends on the lap of the guide bars 'after' the needles which insert the monofilament thread. The movement of these guide bars can take place within the space n, which can be equal to 0, 1, 2, and more needling pitches, which is related to the following stitches of a pillar, tricot , cloth, and velvet. The value of the angle *β* depends on whether the both guide bars, which insert the connectors of the internal layer, make the lap 'before' the needles or not.

We can differentiate the three following cases:

1. 1st case – both needle combs (front and back) manufacture each course of the knitted fabric loops; angle $\beta = 0°$ when the movement is realised from the front to the back of the knitted fabric, or $\beta = arctg \dfrac{B}{g_i}$, when the movement is realised from the back to the front layer.
2. 2nd case – when the connector of the internal layer is arranged along one of the external layers of the knitted fabric, where the angle $\beta = 90°$.
3. 3rd case – a variant in which we have the greatest possibilities of changing the value of the angle $\beta = arctg \dfrac{mB}{g_i}$ and is within the range of $0° < \beta < 90°$.

The knitted fabrics discussed in this article are 3D products, and therefore the arrangement of connectors should be considered in a three – dimensional space. This means that the arrangement of each monofilament in the internal layer depends on the angles *α* and *β* and the thickness g_i of the knitted fabric manufactured.

A real connector is arranged in the shape of an arc of length *lτ*, where *τ* is the angle of the arc ***(Figure 12.a)***. The shape is caused by forces which occur in the knitted fabric loops, as well as in the monofilament segment which connects the external layers. At the design stage, it is difficult to determine the degree of deformation of the connectors, and therefore in order to describe the internal structure, it is easier to use a chord (a straight line which connects the loops of the external layers) of length *l'τ*, instead of an arc. ***Figures 12.b***

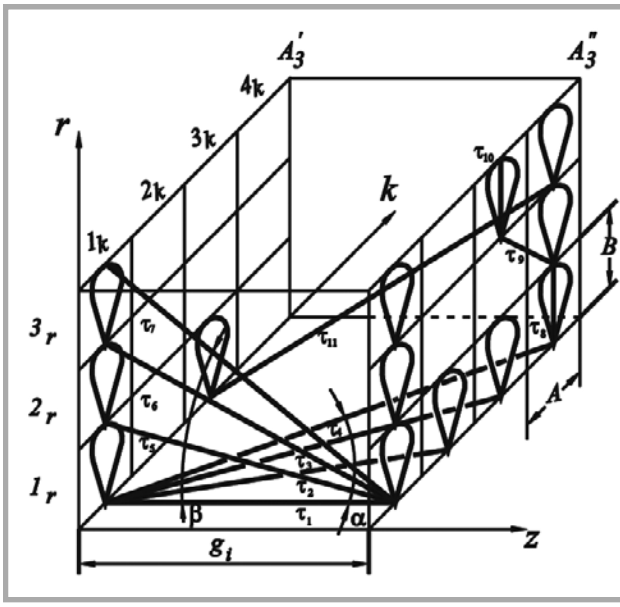

Figure 11. *Configuration of the loop connectors which connect the knitted fabric's external layers; g_i – fabric thickness, A, B – loop dimensions, α, β – angles of the monofilament slopes, $τ_i$ – connectors.*

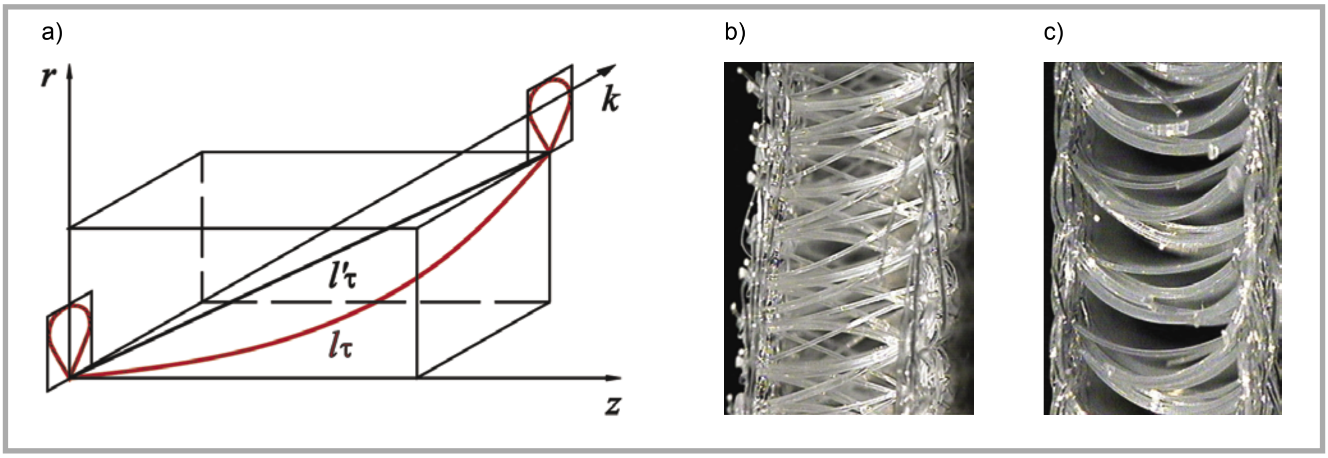

Figure 12. Arrangement of connectors of the internal layer; a) schematic 3D drawing, b) cross – section of a knitted fabric along its courses, c) cross – section of a knitted fabric along its wales; l_τ – arc length of a connector, l'_τ – chord length of a connector.

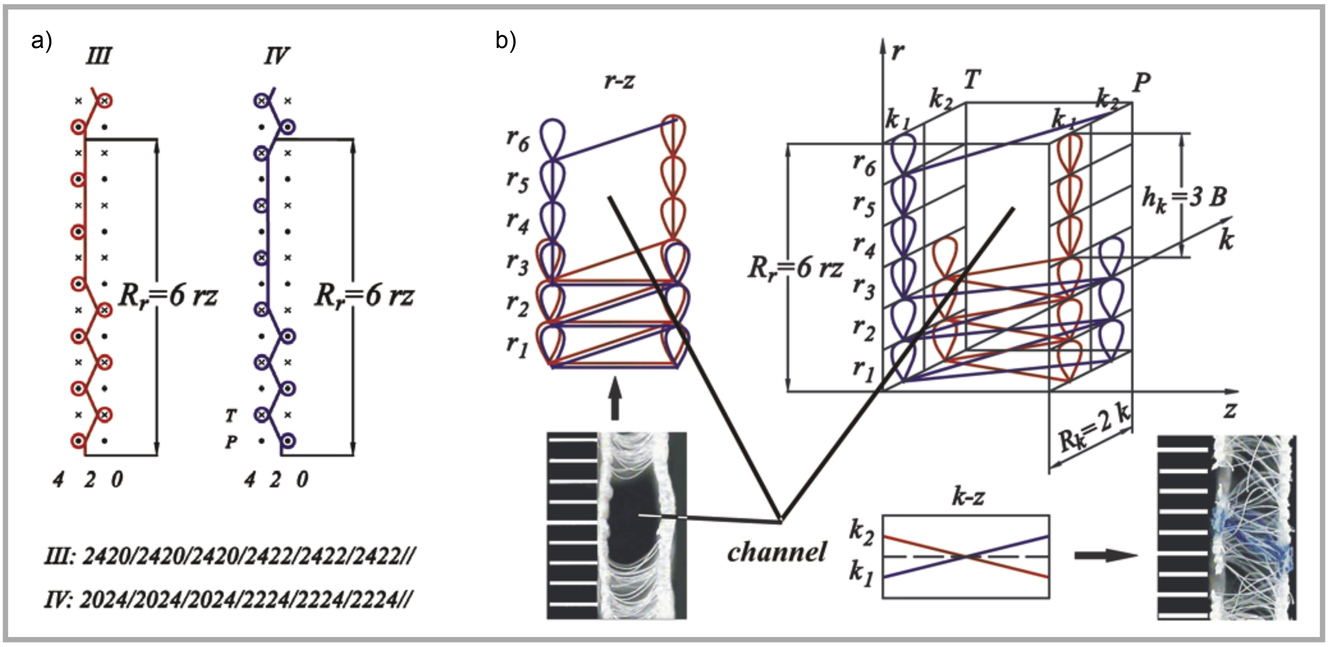

Figure 13. An example of a description of the stitch of a 3D distance warp – knitted fabric with a horizontal channel; a) the hitherto description, b) spatial model of the visualisation together with real cross – sections of the knitted fabric; notations as in Figure 12.

and 12.c present cross – sections of knitted fabrics characterised by a spatial configuration of the connectors in two mutually perpendicular planes.

When we know the width of the wale of loops *A* and the height of courses of loops *B*, we can appropriately select the stitch modelling of the special arrangement of monofilaments in the internal layer of the knitted fabric.

Model of the visualisation of a 3D spatial distance warp – knitted fabric.

Existing descriptions of stitches of 3D distance knitted fabrics are all the same as the schematic description of flat plain knitted fabrics. In the system of alternative rows of dots and crosses ***(Figure 13.a)***, which mark the needles of the front and back needle combs in an analogy to the description of plain stitches for 2D knitted fabrics, the loops formed on the needles across the height and width of the stitch report are subsequently described. This description informs about the order of loop formation and the kind of loops (closed or open loops), as well as the continuity of the connector arrangement between the loops. This description also allows to determine the order of the designing chain links. However, the hitherto used description of the stitches is in no way related to the spatial architecture of the knitted structure. From the above – mentioned description, it is difficult to work out the loop system in the external layers, and it is, certainly, not possible to determine the graphical spatial visualisation of the connector configuration in the internal layer.

The facts described above were the inspiration for the authors of this publication to develop a spatial model for the visualisation of 3D distance warp – knitted fabric ***(Figure 13.b)***.The model of the knitted fabric is considered in the space of the *r-k-z* system. Knitted fabrics in the form of a three dimensional solid is near to the real shape of the spatial architecture of distance knitted fabric. Additionally, for a more precise description of the structure, cross–sections along courses and wales were implemented and confirmed by real photographs taken in this planes. The cross – sections divide the external as well as the internal elements of the knitted fabric structure into two perpendicular planes: *k-z* along the courses and *r-z* along the wales. This description, which is in connection with the schematic drawing of the stitch of the knitted fabric, which is placed on the needles, consists of broader information (than the classical description) for the designer, mainly about the real structure of the product and enables to predict some product properties, for example the bending rigidity, air permeability and thermal protective features.

From the example presented in ***Figure 13***, we can conclude that the graphical simulation of the description of the knitted fabric model , with some simplified assumptions, presents the real structure of the product. The connection of the method presented, which is based on the 'flat' description of the stitch, with the spatial description of the stitch creates a hybrid model.

The description presented in ***Figure 13*** was made manually on the basis of a schematic drawing of the stitch on the needles with the use of an AutoCAD program [10-12]. It would be advantageous to elaborate an algorithm and develop a computer program which would automatically create spatial graphical models of 3D distance knitted fabrics on the basis of information from a schematic drawing of the stitch and parameters of the knitted fabric structure.

Summary

- The three – dimensional spatial geometrical model of a 3D distance warp – knitted fabric describes the structural parameters and selected features of three – and five – layer structures differentiated by the structure of external as well as internal layers.
- New notions (technical terms) of 'spatial a – jours' and 'spatial relives', which describe 3D distance knitted fabrics, were introduced. The structure of both groups of knitted fabrics were defined. The spatial a – jours were determined as structures which are characterised by a spatial system of the solids of the internal layer, which are formed as a result of unconnected external stitches of the knitted fabric. The group of spatial a – jours includes knitted fabrics with longitudinal and transversal channels (ducts), as well as channels which are perpendicular to the knitted fabric surface. A spatial relieve is determined as a knitted fabric which is characterised by uneven external surfaces, between which a layer with differentiated thickness is placed. A special, particular case of such a knitted fabric was described, characterised by only one external layer manufactured using a plain stitch.
- The spatial configuration of the threads of a knitted fabric's internal layer is an essential structural factor of this layer. On the basis of the analysis of the distance warp – knitted fabrics, it was stated that the values of the angles α and β of the diagonals connecting the opposite loops of the fabric depend on the kind of stitch and the thickness gi of the product.
- A spatial model of the visualisation of 3D knitted fabric was elaborated. This is a hybrid model which includes the description of stitches in a 2D plane hitherto used, as well as a graphical spatial model of the knitted fabric in the three – dimensional Cartesian *xyz* system. The model was verified by examples of cross – sections of twenty variants of knitted fabrics manufactured. A spatial algorithm was developed for the description and identification of three –dimensional knitted fabric structures.

The structural model of 3D distance warp – knitted fabric presented in this article is the basis for a broader analysis of the features of such products from the point of view of their mechanical and physiological properties, among others.

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