Systemic Approach to the Design of Knitted Fabric with Three Dimensional Architecture – Part I

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Abstract

Knitted fabrics with complex architecture present an important development potential, especially in technical applications. They can be divided into three groups: multiaxial fabrics, sandwich/spacer fabrics and spatial fashioned fabrics. The main technique used to produce spatial fashioned structures is knitting on a variable number of needles. The correlation of the 3D shape of the product with the 2D geometry of the fabric requires the definition of the basic elements and fashioning (contour) lines. The basic elements are simple geometrical shapes (triangles, rectangles or ellipses) that can be used to divide the 2D plan of the fabric. Considering the 3D shape, the fashioning lines represent section lines that are used to create the plan, where the knitting takes place on a variable number of needles. The basic elements and the fashioning lines can be described using parameters, thus allowing a fabric design that is correlated with the 3D shape intended to be obtained. Another interesting aspect is the modelling of the spatial shape of the fabrics, for which an initial variant is proposed, showing the stress distribution generating the 3D geometry of the knitted surface.

Key words: 3D knitted fabric, spatial fashioning, fashioning line, basic element, modelling

1. Introduction

The shape of textile fabrics/products is an important factor in the design stage, because it influences the selection of raw material, structure and technology. Based on their significant dimensions, textile materials/fabrics can be grouped into:

- 1D materials, for which the length is essential – this group includes fibres and yarns;
- 2D materials that have two determinant dimensions (length and width) – this is the case of the woven, knitted, braided fabrics, as well as non-wovens with constant thickness;
- 3D materials that are built along all three axes – in this group there woven, knitted and braided fabrics with complex three dimensional architecture.

The need for products with complex shape required the adaptation of the textile fabrics and led to the concept of 3D fabrics and three dimensional architecture. The 3D shape of a textile product is not new, but at first it implied the use of assembling technologies. The production of three dimensional fabrics eliminates the ulterior assembling operations (with implications regarding the production time and costs), as well as it offers the possibility of controlling the final product shape from the fabric design stage. The technological developments of the last decades and the introduction of the CAD/CAM systems made possible the production of 3D fabrics with increasing complex shape.

The 3D fabrics are found in different applications, many times a certain destination imposing the shape of the fabric/product. The field of technical textiles is the one where the complex shape fabrics had the most significant development, due to the high level of
the applications, the restrictions imposed by the specific requirements, the process of the high performance raw materials and the need to simplify the subsequent processing. Most known example is the advanced composite materials, for which the reinforcement (preform) is produced with the final shape of the composite.

Knitted fabrics have a good potential for the production such complex shapes due to:
- Their high formability, determined mainly by their high elasticity;
- The high level of complexity for the shapes that can be knitted;
- The existing machinery can be used without significant modifications;
- The control of fabric behaviour through structure and structural parameters.

The spatial knitted fabrics are obtained using both technologies – weft and warp knitting. The weft knitted fabrics produced on flat machines present the best possibilities regarding shape diversity and complexity.

A classification of the 3D knitted fabrics includes the following types:

1. **Multiaxial fabrics**, characterised by the presence of successive layers of yarns within the fabric structure. The most important are the warp multiaxial fabrics (see Figure 1), with layers of yarns inclined at preset angles, from 0\(^\circ\) (weft yarns) to 90\(^\circ\) (warp yarns). Such fabrics are characterised by very high thickness and the reinforcement on preset directions [1]. Their main destination is as reinforcement for composite materials, the yarns used to make the layers being glass and carbon. The multiaxial weft knitted fabrics are still in laboratory phase, requiring new types of machines. The main problem is the complicated process of yarn feeding.

![Figure 1. Multiaxial warp knitting technology (Liba)](image)

2. **Sandwich/spacer knitted fabrics** are made of two independent fabrics connected through yarns or knitted layers. The warp knitted fabrics with such a structure are known as spacer fabrics [1, 2], the connection being made only with yarns. The warp knitting technology is suited for the production of spacer fabrics with open and/or closed structure for the external fabrics, as exemplified in Figure 2. The fabric thickness depends on the trickplate distance, going over 5 cm. If special monofilament yarns are used the connection, the spacer fabrics present an excellent bending recovery that recommends them for end-uses such as backpacks, shoes, mattresses, etc.

In case of weft knitting, the sandwich fabrics are connected using yarns or knitted layer [3, 8]. The connection through yarns offer limited possibilities of structural diversification, while the fabric thickness is limited. The sandwich fabrics with connection through knitted layers (single or double) are characterised by a complex geometry, for which the shape and dimensions of the cross section depend on the connecting layer. The length of this layer can reach 10 cm, while the shape can be different, from rectangular to elliptic, V shaped, trapeze, etc.
Figure 2. Examples of spacer fabrics with closed and open structure

The main destination for these structures is preforms for advanced composites, produced with glass/carbon fibres. An important aspect is the volume fraction due to the structure of the knitted layers (produced on selected needles 1x1).

3. **Spatial fashioned fabrics** are fabrics where the 3D geometry is obtained through fashioning, when the knitting is carried out on a variable number of needles [3-7]. The 3D geometry is generated by the different amount of rows knitted along the panel width, the surplus stitches being placed spatially. These fabrics are produced on electronic flat knitting machines for which the carrier course is variable. The paper focuses on this type of fabrics.

Figure 3. Examples of sandwich fabrics with connection through yarn and knitted layer

2. **3D fashioned knitted fabrics produced on flat knitting machines**

The spatial fashioning of the knitted fabrics is based on the need to produce fabrics with complex shapes that are similar to the shape of the final product. Even if a certain degree of spatial geometry can be obtained by using modules of structures with different patterns or by dynamic stitch length, the technique of spatial fashioning is the only one that has no limitations with regard to the shape complexity and dimensions. This technique (also known as ‘flechage’) is based on knitting courses on all working needles and courses on a variable number of needles, determining zones with different amount of stitches. The zones with the highest amount of stitches will have in the end a spatial geometry.

The knitted fabrics with complex architecture are used for clothing, as well as for technical applications, again most common being preforms for advanced composite materials. The literature contains a significant number of examples of spatial knitted fabrics, but it must be emphasised that their approach is direct, based on practical situations and presenting the production aspects.

A classification of the spatial fashioned fabrics must take into consideration the 3D shape of the product. There are fabrics with different shape, such as: hemispherical and spherical fabrics; frustum of a cone and hyperboloid fabrics; tubular shaped fabrics – straight (T shape) or bent; parallelepiped and pyramid fabrics; discoid fabrics; fabrics with other shapes, derived from the ones mentioned above.
Figure 4 illustrates the correlation between the 3D shape of the product and the 2D plan of the fabric, emphasising the most significant elements for knitting. The knitting direction is very important when designing a 3D fabric. Knitting along the transversal or longitudinal direction of the final shape determines the knitting programming, the plan aspect and furthermore the specific behaviour of the fabric in the product. In some cases, only one knitting direction with regard to the product shape is possible, the other option being technologically not feasible.

The fabric 2D plan is a rectangular area where are positioned the fashioning lines that define the final 3D shape of the product. Such a 3D fabric is obtained by placing more fashioning lines with certain characteristics, forming geometric basic forms that are repeated within the plan or not (as is the case for parallelepiped forms).

### 2.1. Fashioning lines

The fashioning lines can be defined from two points of view – of the final 3D shape and of the 2D fabric plan. When considering the fabric plan, the fashioning lines define where the knitting will be carried out on a variable number of needles, these zones generating the spatial geometry. The lines have two components, corresponding to decreasing the number of working needles and the other to increasing them. In the fabric, these two lines become one, the actual fashioning line. Figure 5 exemplifies such a line in a knitting programme (Stoll), underlining the two stages of the fashioning process. The fashioning lines can be classified considering the following criteria:

- **Line form**
  - Straight – with constant increment of the fashioning line (see Figure 5)
  - Curves, actually defined based on a polygonal contour – with variable increment of the fashioning line, creating a different 3D geometry depending on the line increment (see Figure 6).

- **Line symmetry**
  - Symmetrical – the two component lines are symmetrical. This is the most common case because it generates the strongest 3D effect. The symmetry of the fashioning line is reflected in the spatial geometry of the fabric.
Non-symmetrical – the line corresponding to needles that stop working is not symmetrical with the line corresponding to the same needles restarting to work. When reintroducing the needles, the line can have a different slope or the slope can be 0, if all needles start working in the same row, as illustrated in Figure 7.

Each type of fashioning line will create a 3D geometry with its specific height and shape. In order to be able to control the final 3D shape of the product, it is necessary to know what effect each type of fashioning line generates in a fabric.

2.2. Characterisation of 2D basic elements

If the final spatial shape is considered, the fashioning lines represent the section lines of the shape, defining the **basic 2D element** on which the sectioning is based, in order to determine the form of the plan.

The basic elements are characterised by a simple geometrical form (ellipse, triangle, and rectangle) and their single or repeated positioning defines the fabric plan in the fashioning zones. This idea of generating 3D shapes using basic elements allows a systemic approach to the knitted fabrics with spatial geometry and their design based on simple, easy to calculate geometric forms. The triangles represent knitting zones on a variable number of needles and correspond to straight fashioning lines, while the
rectangles mean the knitting is carried out on a constant number of needles. The ellipse can be considered a polygonal fashioning line with variable increment. A plan can be divided into simple basic elements, as the one described, or into composed elements that will diversify the fashioning possibilities with regard to final shape.

The ellipse is the basic 2D element in case of the hemispherical and spherical shapes (see Figure 8), while triangles and rectangles are used for frustum of a cone and hyperboloid, as well as for tubular bent shapes and discoid, as exemplified in Figures 9 and 10 [4, 5, 6]. The triangles and rectangles can be used also for parallelepiped (see Figure 11). The number of repeats for the basic elements defines the shape and the final dimensions of the knitted fabric.

The advantage of using basic elements when designing such a fabric is that the 2D plan is easy to generate and characterise based on the 3D shape.

3. Design of knitted fabrics with spatial geometry

3.1. Parameters of the fashioning lines

The fashioning lines can be defined using a set of parameters for the design of knitted fabrics with spatial geometry.

From the knitting programming point of view, a fashioning line can be defined using the line increment – the number of needles that stop/start working in the fashioning zone \( \Delta a \) and the number of rows with the same number of needles working \( \Delta r \). By repetition, the line increment gives the line dimensions (the number of needles and rows for the fashioning line).

The fashioning line is geometrically characterised by dimensions (height \( h \) and width \( l \)) and slope (the angle of the line with the row direction \( \alpha \), see Figure 12).
The dimensions of a fashioning line will be:

\[ h = N_r \times B = N_r \times \frac{50}{D_v} \]  
\[ l = N_s \times A = N_s \times \frac{50}{D_o} \]

Where: 
- \( N_r \) = number of rows in the fashioning line
- \( N_s \) = number of wales in the fashioning line
- \( B \) = stitch height (mm)
- \( A \) = stitch pitch (mm)
- \( D_v, D_o \) = stitch density [wales/50 mm] and [rows/50 mm]

The length \( L \) of the fashioning line is calculated based on its dimensions:

\[ L = \sqrt{h^2 + l^2} \]

(3)

The line slope (see Figure 14) will influence the 3D geometry of the fabric. A higher slope will determine a stronger 3D effect. The slope is given by the following relation:

\[ \tan \alpha = \frac{h}{l} = \frac{N_r \times B}{N_s \times A} = \frac{N_r}{N_s} \times \frac{C}{C} = \frac{\Delta r}{\Delta a} \]

(4)

Where: \( C = \) stitch density coefficient = \( \frac{B}{A} \)

The use of stitch density coefficient to determine the line slope allows connecting it to the stitch dimensions, thus determining the parameters of the fashioning line based on the structural parameters.

Another important parameter is the missing index (the number of rows when a stitch misses due to working on a variable number of needles). It varies from \( i_{\text{max}} = N_r \) to \( i_{\text{min}} = \Delta r - 1 \). This index is a significant parameter because it reflects the increment of the fashioning line, and on the other hand it represents a limiting factor for the knitting process. The variation of the missing index along the fashioning line also indicates the variation of stress within the fabric.

The amplitude of the spatial shape \( H \) refers to the 3D geometry of the fabric and represents its height in reference to fabric plan, as illustrated in Figure 13. The amplitude reflects the spatial fashioning and allows for a comparison between fabrics regarding the 3D geometry. It depends on: the dimensions and slope of the fashioning lines, the stitch dimensions and the specific spatial geometry of the 3D shape. Because of the way the fabric takes the 3D form, the amplitude \( H \) cannot be equalled to the fashioning line height \( h \).
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