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Three-dimensional Computer Simulation of Warp Knitted Spacer Fabric

Abstract

The main objective of this paper was to simulate the three-dimensional structure of warp knitted spacer fabric using computer technology. For this purpose, the geometric structure of warp knitted spacer fabric was investigated. Specifically, a 3D spacial stitch model of warp knitted spacer fabric is developed using non-uniform rational B-spline(NURBS) curves and surfaces. Since the stitches in real fabric are usually inclined, the offset rule of special stitches is employed in order to simulate the stitches more realistically. Then the offset calculation formulas for each given point in the 3D stitch model are obtained. Finally 3D computer simulation of warp knitted spacer fabric is achieved and some simulation images of this kind of fabric are generated on the computer. The mechanism developed in this paper can model the 3D structures of common warp knitted spacer fabric interactively and accurately.

Key words: *warp knitting, spacer fabric, stitch model, pile yarn, 3D simulation.*

Warp knitted spacer fabric, produced on a double-bar Raschel warp knitting machine, is one kind of three-dimensional textile structure, which consists of two surface layers and a spacer layer. The pile yarns connecting two independent surface layers cross over the space to form a special 3D structure which enables the fabric to obtain versatile properties, such as air permeability, good compressive characteristics, and thermoregulation.

Studies on the structures and properties of spacer fabric have been carried out in depth with the wide application of spacer fabric [1 - 6]. During such research, researchers should gain substantial knowledge of the geometric structures of spacer fabric, which can be obtained by observing true fabric. However, spacer fabrics are so complicated and of great variety that it is quite inconvenient to observe true fabrics. A simple and effective method is to observe a structural model of spacer fabric, through which the fabric properties can derived by researchers.

For this 3D fabric, 2D simulation, which models one side of the fabric only, is not practical here. Therefore, in order to observe and study the structure of spacer fabric better, it is best to develop a 3D structure model and to simulate spacer fabric from different views.

Warp knitted spacer fabric has been developed for many years, but there have been few studies on the 3D simulation of warp knitted spacer fabric. In recent years, some researches in this field have been gradually carried out, such as the 3D simulation of plain warp knitted spacer fabric in ProCad software, developed by TEXION Software Solutions in Germany [7], and the geometrical model of spacer fabric developed by Polish researchers [8 - 10]. In order to speed up research on the 3D simulation of spacer fabric, the aim of this paper is to build a solid structural model for warp knitted spacer fabric after research on the spatial structures thereof , and then to achieve 3D computer simulation.

Structure of warp knitted spacer fabric

One of the special features of warp knitted spacer fabric in its structure is that the two surface layers connected by pile yarns form a sandwich structure, as shown in *Figure 1*. The surface layers are knitted on the front and back needle-beds of double-bar warp knitting machines, respectively, and can be knitted into any kind of mesh or plain structure to get the dimensional, mechanical and comport properties required; whereas in order to connect the surface layers together, the pile yarns must lap on both the front and back needles. During knitting, the pile yarns form stitches successively on the front and back needles; thus owing to the effect of the draw-off mechanism, the stitches formed on the front needles will be a half-stitch higher than that formed on the back needles in the same wale (*Figure 2* [6]). Furthermore, because the pile yarns are in a tensioned state during knitting, they tend to relax and bend op-
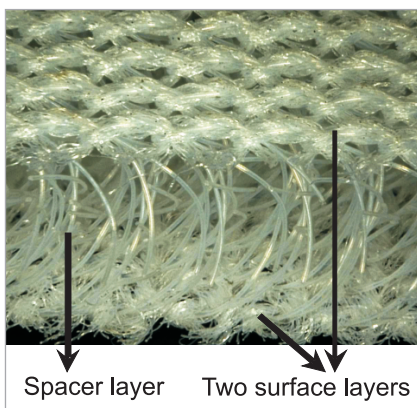

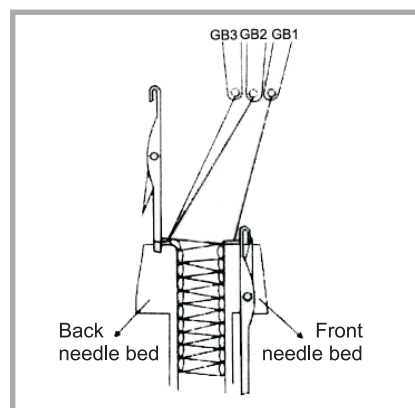*Figure 1. Hierarchical chart of warp knitted spacer fabrics.*

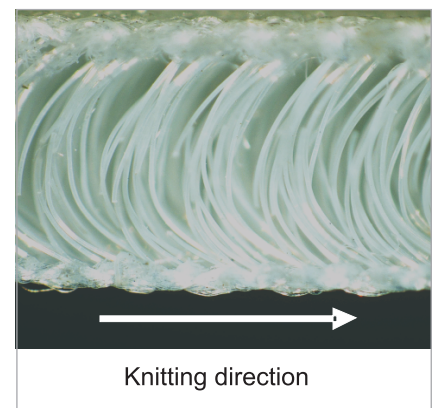*Figure 2. Knitting process of spacer fabrics.*

Figure 3. Profile section of warp knitted spacer fabric.

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Zhang L-Z, Jiang G-M, Miao X-H, Cong H-L. Three-dimensional Computer Simulation of Warp Knitted Spacer Fabric.
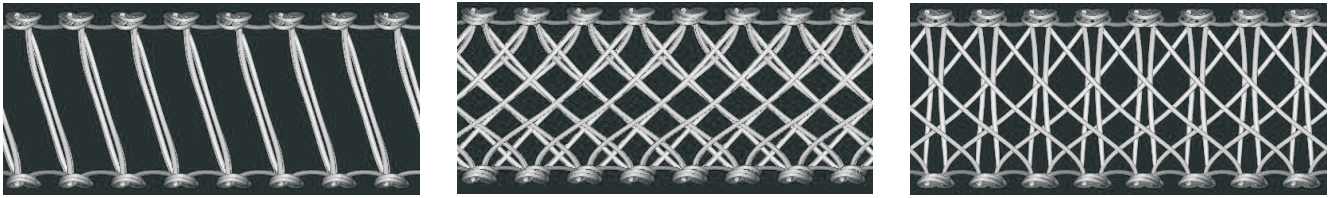*FIBRES & TEXTILES in Eastern Europe* 2012; 20, 3(92): 56-60.

Figure 4. *Common effects of the cross section of warp-knitted spacer fabrics: a) parallel type, b) crossed type, c) combined type.*

posite to the knitting direction, as shown in *Figure 3*.

In order to satisfy the different end-use requirements, pile yarns can be knitted with different structures and the cross section of spacer fabrics be made to present different effects. The common effects are the parallel type, crossed type and combined type (*Figure 4*) [11]. Cross-section shapes are formed by the pile yarns lapping on the front and back needles, thus varying the lapping methods will lead to different cross-section shapes. The cross-section shape will affect spacer fabric properties, such as the compressive property and stability property. For instance, fully threaded pile yarns using the lapping movement 1-0-1-2 can form a parallel structure between the two surface layers, as well as the lapping movement 1-0-4-5. However, the inclination angle of pile yarns in the former case is smaller than that in the latter, which will affect the stability of spacer fabrics.

Spacial stitch model of pile yarn

Because of the special 3D structure of spacer fabric, the special stitch shape of spacer structure is different from that of the single-bar warp knitted structure, the main difference being the direction of underlap. Moreover, in order to sustain the space between the two surface layers, monofilament yarns with good bending rigidity are normally used as pile yarns, such as polyamide and polyester.

3D linear model of pile yarn

According to the structural properties of spacial stitch, its 3D linear model (shown in *Figure 5*) can be built based on the following assumptions:

1) Stitch height $|CE| = h$. The value h can be obtained by calculating the course-spacing without considering the stitch inclination.

2) Stitch width $|BD| = 0.4 h$. This value is equal to that in the single-bar stitch model built by O. Goktepe [12].

3) $|OE| = 0.65 h$. This length shows the distance from the widest section of the stitch to the root.

4) The underlap height $|F'M| = 0.5 h$. This shows the difference in the value of the stitch height on the same course between the front and back surface layers, determined by the knitting characteristics.

5) The underlap length in the course direction (x-axis) $W = m$ (needle number that the underlap crosses)$\times w$ (distance between two adjacent wales). This assumption is based on that fact that the stitch wales on the two surface layers are aligned.

6) The intercrossing length of stitches in the front and back layers in the wale-wise direction: $b = |C'E| = |CE'| = 0.2 h$. This assumption is based on observation.

7) Stitch-bend length $|LN| = 2d-(i-1)\times(d/2)$. i refers to the bar number.

8) Stitch-bend height $|CL| = 0.65 h$. The value denotes the position of the maximum loop bend.

9) The space thickness $|ME| = s$, e.g. the underlap length along the z-axis, which can be obtained by measuring the thickness of the spacer fabric.

Solid pile yarn model

The materials used in the spacer layer are normally monofilaments of circular cross-section, which are smooth and uniform. In this paper, non-uniform rational B-spline (NURBS) curves and surfaces are used to simulate the solid yarn because they can represent the bending and connection of true yarns better [13].

To depict the pile yarn's special shape with NURBS surface, two parameters are required, which are defined as u and v. The central axis determines the former parameter of the NURBS surface, and the cross-section determines the second one, as shown in *Figure 6* (see page 58). The coordinates of the points referring to the cross-section can be calculated by the following formula [14]:

$$\tilde{C}(\theta) = \begin{pmatrix} \underbrace{x_1 - r\cos\theta\frac{a_2}{\sqrt{a_1^2+a_2^2}} - r\sin\theta\frac{a_1 a_3}{a\sqrt{a_1^2+a_2^2}}}_{x} \\ \underbrace{y_1 + r\cos\theta\frac{a_1}{\sqrt{a_1^2+a_2^2}} - r\sin\theta\frac{a_2 a_3}{a\sqrt{a_1^2+a_2^2}}}_{y} \\ \underbrace{z_1 + r\sin\theta\frac{\sqrt{a_1^2+a_2^2}}{a}}_{z} \end{pmatrix}$$

(1)

In *Equation 1*, x_1, y_1, z_1 refers to the point in the central axis; a_1, a_2, a_3 is the tangent vector of this point, r denotes the yarn radius, and θ represents the central angle in the cross-section. It should be noted that θ is constrained to $0 \leq \theta \leq \frac{5\pi}{2}$
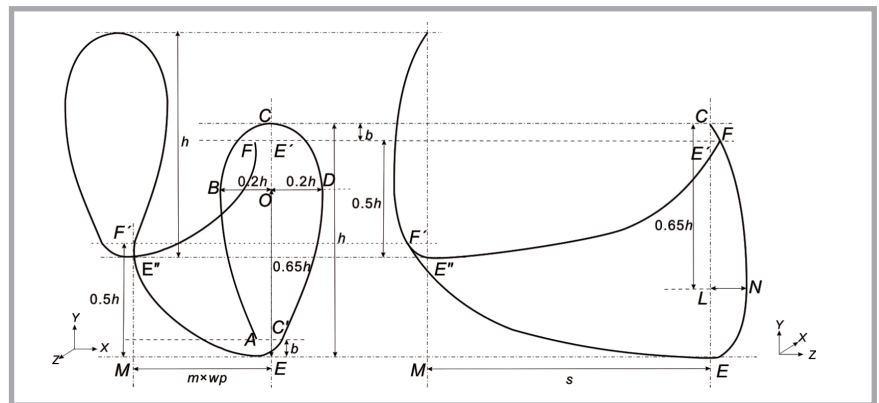

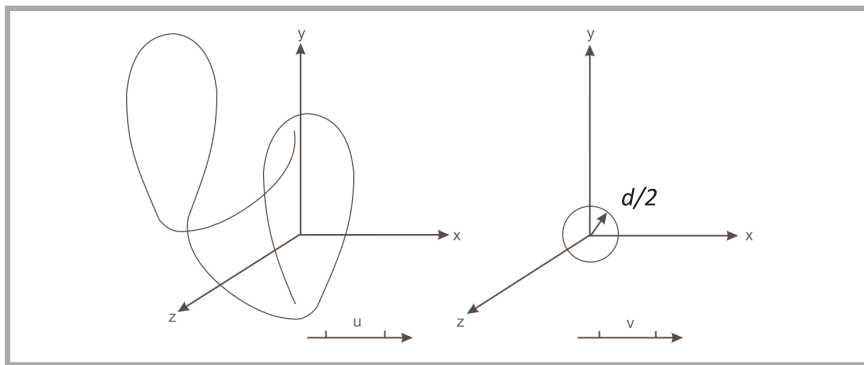*Figure 5.* *3D stitch model of spacer fabrics and its dimensions in the fabric plane and fabric cross section.*
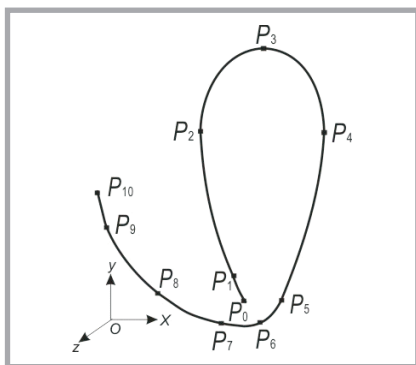
Figure 6. *u and v parameters for 3D stitch model.*

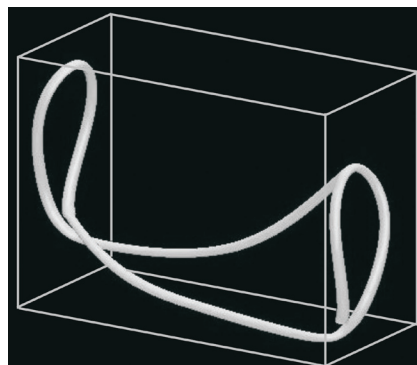**Figure 7.** *Control points of 3D stitch model.*

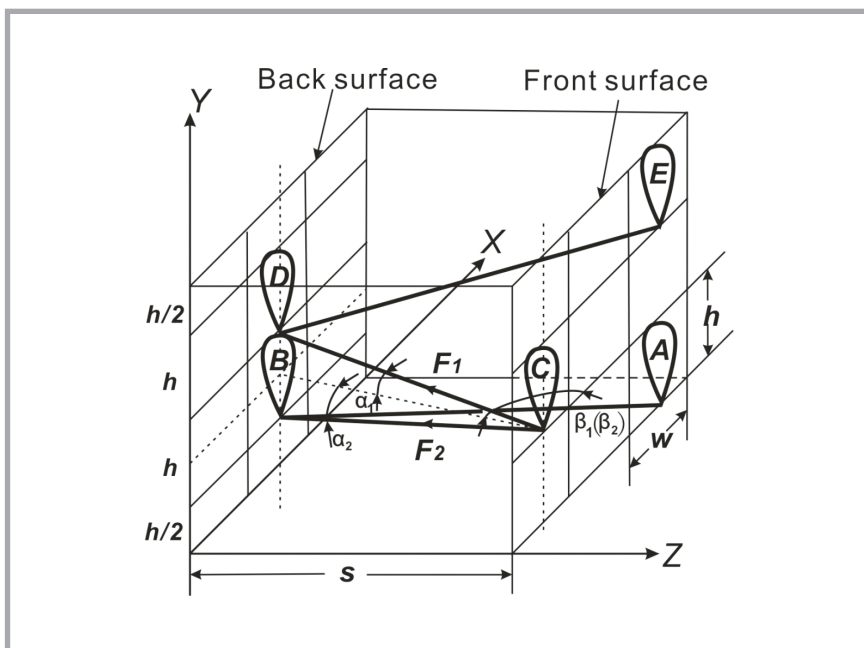**Figure 8.** *3D Computer simulated image of spacer stitch.*

Figure 9. *3D structures of spacer stitches and their force diagram. h - stitch height, w - stitch width, s – spacing distance; α_1, α_2, β_1, β_2 - inclined angles of spacer yarns.*

to form a closed circle. The program generates the co-ordinates of the first control point by putting zero as the value of θ in *Equation 1*. Then it calculates the co-ordinates of the subsequent points by increasing the value of θ by $\pi/4$ for each point until θ equals to $5\pi/2$. Therefore,

for the second parameter, v, the number of control points is set to 11 and the knot sequence for a circle cross-section is {0,1,2,3,4,5,6,7,8,9,10,11,12,13,14}.

When depicting the spacial stitch shape with NURBS curves, the control points

used should be as few as possible in order to promote the speed of forming images on the computer. In this research, eleven control points are used to control the shape of a spacial stitch (*Figure 7*). NURBS curves used to model cubic shapes do not pass through all of the control points defining the stitch shape. Therefore, to control the stitch shape better here, the NURBS interpolation algorithm [15] is applied to insert two aided vertices between two adjacent given points. Then the control points concluding the original given-point sequence can be obtained, and a cubic NURBS curve formed by this control point sequence passes through the original given points. *Figure 8* shows two connected spacial stitches modelled on a computer according to the given-point coordinates defined.

■ **Calculating the stitch offset**

In spacer fabrics, especially in net fabrics, the stitches are not erect in the surface layers, but inclined somewhat. Stitch inclination is closely related to yarn tension, influencing the degree of stitch inclination. Yarn tension is caused by many factors such as the let-off tension of knitted fabrics and the thickness of materials. The bigger the yarn tension, the bigger the stitch inclination. Moreover the structure of spacer fabrics can also influence stitch inclination. When the thickness of materials and stitch density are constant, the stitch inclination is mainly influenced by the length and direction of underlaps. To simplify the offset regulation of stitches and then to calculate the offset, the following assumptions are made:
a) Stitch offset is mainly caused by yarn tension and the stress of underlaps.
b) Only the offset in the horizontal direction is considered, and the longitudinal deformation of stitches is neglected.
c) The knitting position of stitches, i.e. the position where stitches are not inclined is defined as the standard position.
d) The offset of stitches formed on the current needle is caused by the tension of all the stitches on this needle, hence the stitch offset should be the offset sum of all the stitches on the current needle.

Formula derivation of stitch offset

The spatial structure of spacial stitches in a fabric is shown in *Figure 9*, in which we assume that the plane where the two

surface layers are placed is the *X-Y* plane, and that perpendicular to the surfaces, i.e. the plane which the spacer layer is placed on, is the *Y-Z* plane. According to the above study on the structure of spacer fabrics, the stitches on the back surface are a half-stitch higher than those of the same course on the front surface. *Figure 9* shows that compared with the front-surface stitches *A* and *C*, the back-surface stitches *B* and *D* are $h/2$ higher, respectively.

Let us take stitch *C* as an example to analysis the force condition of spacer stitches, and then calculate the stitch offset. The root of stitch *C* receives tension F_1 and F_2 which are respectively caused by the two underlaps connected to the stitch, which results in the lateral offset of the stitch on plane *X-Y*. Thus, the tension *F* and offset d_x that stitch *C* received in the lateral direction can be obtained using the following formulas:

$$F = F_1\cos\alpha_1\cos\beta_1 + \\ + F_1\cos\alpha_2\cos\beta_2 \qquad (2)$$

$$d_x = kF \qquad (3)$$

In *Equation 3*, *k* refers to the offset coefficient of stitches in the lateral direction, which is influenced by the thickness of materials, the let-off tension and so on. In this program, the value of *k* can be adjusted by the users according to the fabric properties. In *Equation 2*, α_1 and α_2 respectively refer to the angles formed by the two underlaps connected to stitch *C* and plane *X-Z*; β_1 and β_2 respectively refer to the angles between the projection of the two underlaps on plane *X-Z* and plane *X-Y*. The four angles are given by

$$\tan\alpha_1 = \frac{h/2}{s/\sin\beta_1} \qquad (4)$$

$$\tan\beta_1 = \frac{s}{n_1 w} \qquad (5)$$

$$\tan\alpha_2 = \frac{h/2}{s/\sin\beta_2} \qquad (6)$$

$$\tan\beta_2 = \frac{s}{n_2 w} \qquad (7)$$

In these formulas, n_1 and n_2 refer to the numbers of needling pitches, and *s* refers to the space thickness. From the above formulas, it can be seen that the angles α_1, α_2, β_1 and β_2 are related to the spacial distance and the stitch's dimension, i.e. the density of the spacer fabric. For the same spacer fabric, the spacial distance and fabric density are determined; hence

the force on the stitches is only related to the underlap length, and the stitch offset will be influenced by the underlap length. In different fabrics, the stitch offset is affected by the special distance and fabric density.

Warp knitted spacer fabrics are normally knitted on a Rashel machine with more than one bar, which leads to more than one stitch formed in the same knitting position. Therefore, the stitch offset in a certain knitting position should be the sum of all the stitch offset. Based on this, the formula for the stitch offset can be rewritten as

$$d_x = \sum_{i=1}^{n} k_i F_i \qquad (8)$$

where *n* is the total number of stitches formed in the same position.

Calculating the offset of given points of the 3D stitch model

In the 3D stitch model of spacer fabric, eleven given points defining the stitch are distributed in different positions, and receive different forces. According to the positions of the eleven points in the stitch model, they can be divided into three groups for force analysis, whose offset can be determined.

From *Figure 7* it can be seen that the five points P_0, P_1, P_5, P_6 and P_7 are located in the stitch root, and they are subject to the forces caused by the underlaps connected to the stitch on the current course (*j*);hence their offset can be represented as

$$d_{xc,j} = \lambda \sum_{i=1}^{n} k_{ic} F_{ic,j} \qquad (9)$$

where λ is the accommodation coefficient of the offset, used for fine tuning the offset of every point.

Points P_2, P_3 and P_4 lie on the top of the stitch and are subject to the forces caused by the underlaps connected to the next course (*j*+1); their offset may be represented as

$$d_{xc,j+1} = \lambda \sum_{i=1}^{n} k_{ic} F_{ic,j+1} \qquad (10)$$

Points P_8, P_9 and P_{10} are located between the two surface layers. The forces put on these points are mainly from the underlaps connected to the current course on the other surface layer. Thus their offset can be represented as

$$d_{xo,j} = \lambda \sum_{i=1}^{n} k_{io} F_{io,j} \qquad (11)$$

The offset of each point is calculated by the formulas above. In order to obtain the final coordinates after the stitch inclined, they need to be added to the vector coordinates of each point.

■ Simulation results

Based on the stitch model of spacer fabrics, 3D computer simulation of warp knitted spacer fabrics can be achieved with the Visual C++ language [16, 17] and the OpenGL tool [18, 19]. In this program, after inputting the chain notation and the threading of each bar in the interactive user interface, the 3D structure of spacer fabrics can be simulated. *Figure 10* shows a 3D simulation image of warp knitted spacer fabric knitted by three needle bars.

Through adjusting the offset coefficient of stitches in the lateral direction, as well as the material specification and yarn tension, the structure of spacer fabrics can be truly simulated in this program. *Figure 11* (see page 60) represents a computer simulation image of the honeycomb structure.

The lapping track of pile yarn can be clearly seen in the varied threading, such as void threading and threading colour yarn. For instance, take the pile yarn, whose chain notation is 1-0-1-2/2-3-2-1//, for example, the lapping track of the color yarn is shown as deep-color yarn in *Figure 12* (see page 60).

In addition, according to the various applications of spacer fabric, there are great differences in the spacing distance between two surface layers, varying between 2 mm and 60 mm [20]. Therefore users can adjust the spacing distance by
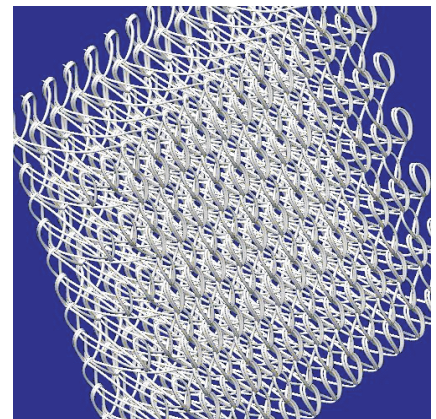

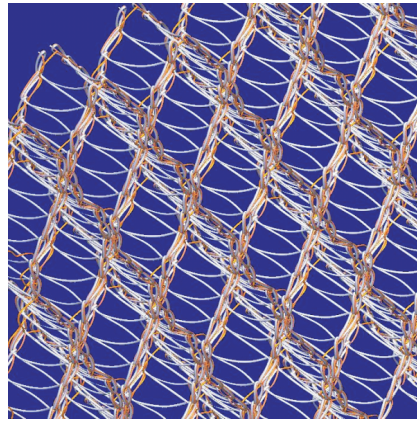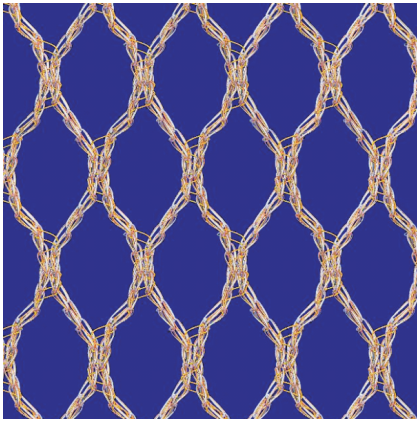*Figure 10. 3D computer simulated image of warp knitted spacer fabric.*

Figure 11. *3D computer simulated image of honeycomb structure: a) front view, b) resolved view.*

Figure 12. *3D computer simulated image of spacer fabric with various threading.*

inputting a parameter in the user interface. Moreover, the 3D computer generated images of spacer fabrics can be rotated and zoomed. ***Figure 13*** shows the cross section of spacer fabric before being pressed and after pressing.

■ Conclusions

Based on the research on the structure properties of warp knitted spacer fabric, a 3D model of a spacial stitch is built using NURBS curves and surfaces. At the same time, considering the real shape of stitches, the offset regulation of stitches is summarised, and the calculation formulas of the stitch offset are obtained. Finally, a 3D computer simulation of spacer fabrics is achieved based on the platform of Visual C++ and usage of the OpenGL library. The simulation results represent the perfect application of NURBS for the 3D simulation of warp
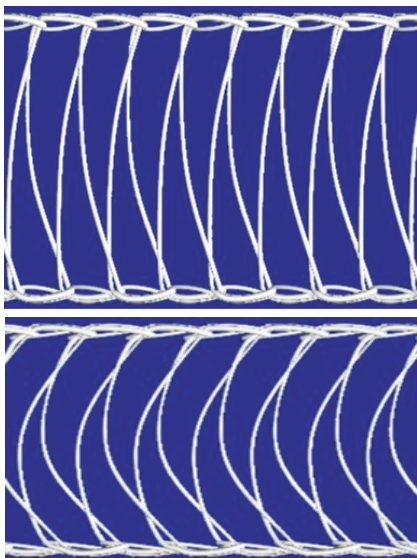

Figure 13. *Computer simulated image of profile section of spacer fabric: a) before pressing, b) after pressing.*

knitted spacer fabrics. The lapping track of the pile yarns can be clearly seen from the computer generated images. These 3D images will help beginners recognise the structures of spacer fabrics better. For fabric property researchers, the images can provide a numerical analysis model for them. With the help of 3D simulated images, researchers can study spacer fabric properties more conveniently.

Because of the complicated structure and various types of spacer fabrics, the current research is limited. During the following study, more factors influencing the realistic simulation of spacer fabrics, for example material qualities, will be considered, with the hope of spreading the application of the stitch model and make the simulating effect better.

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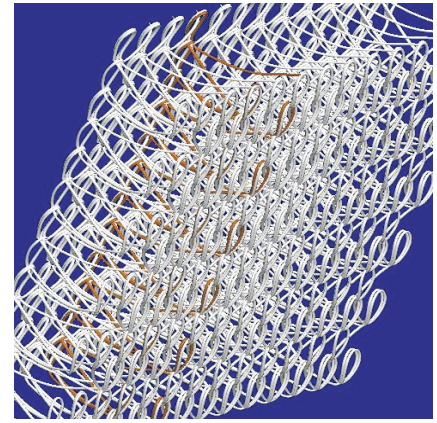7. Karl M. ProCad Warpknit 3D- A New Dimension in Displaying and Simulating Lappings, *Kettenwirk-Praxis* 2008; 3: 36-37.
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