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Macro-Modelling of Rib-Knitted Tubular Parts
Makromodeliranje rebrasto pletenih cevastih sestavnih delov

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Abstract

The aim of the research was to improve the process of knitted products design. The use of modern software helps us predict the physical and mechanical behaviour of materials, using their three-dimensional models. A macro-model of rib-knitted tubular parts was developed in the study. This model allows its implementation into algorithms, describing the peculiarities of the stretching process. Recent findings in the field of 3D modelling and simulation of knitwear behaviour aim at working with models of different scales of structural hierarchy. The use of macro-models provides the opportunity to simplify the geometry and significantly reduce the time required for simulation. Rib stitch structures are among the most popular weft-knitted ones. When using threads of usual stretchability (with breaking elongation that does not exceed 10–12%), the stretchability of some rib stitch structures in the course-wise direction can reach up to 350% and even more. When stretched in the course direction, rib-knitted stitches undergo a number of stages. The stretching process includes: decreasing the width-wise curling; mutual shifting of knit and purl stitches; reducing the curvature of the loop feet and loop heads; pulling the yarn from the loop legs to the loop feet; stretching of the yarn. The assumption was made that such parts of knitted garments as cuffs and borders on sweaters, cuffs on socks, where rib stitch patterns are used, can be described as thin-walled elastic shells. A part of a human body surface, covered with a rib-knitted garment part, can be approximated by a truncated cone. The mid-surface of the shell can be represented as a ruled surface created upon a set of Bezier curves, located along the circumference of the upper and lower bases of the truncated cone. The mathematical description, elaborated in the course of the research, was used for the computer program LastikTube, which was developed to create 3D macro-models of ribbed tubular garments.

Keywords: Rib stitch structures, macro-models, sock cuff, 3D modelling

Izvleček

Cilj raziskave je bil izboljšati proces oblikovanja pletenih izdelkov. Sodobna programska oprema nam z uporabo tridimenzionalnih modelov materialov pomaga predvideti njihovo fizikalno in mehansko obnašanje. V študiji je bil razvit makromodel rebrasto pletenih cevastih sestavnih delov. Model omogoča izpeljavo v algoritme, ki opisujejo posebnosti raztezanja. Najnovejša spoznanja na področju 3-D modeliranja in simulacije obnašanja pletenin so namenjena delu z modeli na različnih ravneh strukturne hierarhije. Uporaba makromodelov omogoča poenostavitev geometrije in znatno skrajšanje časa, potrebnega za simulacijo. Rebraste strukture so med najbolj priljubljenimi votkovnimi pletivi. Pri uporabi niti običajne raztegljivosti (s pretržnim raztezkom pod 10–12 %) lahko raztegljivost nekaterih rebrastih struktur *v smeri zančnih vrst seže do 350 % in celo več. Pri raztezanju v smeri zančnih vrst gredo rebrasta pletiva skozi več faz. Raztezanje zajema: zmanjšanje vihanja po širini; vzajemno premikanje levih in desnih zank; zmanjšanje ukrivljenosti igelnih in platinskih glav zank; odvzemanje preje od krakov zanke k platinski glavi zanke in raztezanje preje. Domnevali smo, da lahko dele pletenih oblačil, kot so rokavne in pasne obrobe na puloverjih in robovi nogavic, kjer so uporabljene rebraste pletene strukture, opišemo kot tankostenske elastične lupine. Del površine človeškega telesa, ki je prekrit z rebrasto pletenim delom oblačila, lahko poenostavljeno prikažemo kot prisekani stožec. Sredinsko površino lupine lahko predstavimo kot ravno površino, ustvarjeno s pomočjo niza Bezierovih krivulj, ki se nahajajo vzdolž oboda zgornje in spodnje osnovne linije prisekanega stožca. Matematični opis, izdelan med raziskavo, je bil uporabljen za računalniški program LastikTube, ki je bil razvit za izdelavo 3-D makromodelov rebrastih cevastih oblačil.*

Ključne besede: rebrasta pletena struktura, makromodeli, rob nogavice, 3-D modeliranje

1 Introduction

The challenge of designing knitwear with predicted properties is widely discussed in the scientific community. Evidently, the demands for the quality and comfort of clothing are constantly rising. Some of the most important properties of apparel that affect the level of human comfort in the process of wearing clothes are air permeability, hygroscopicity and tactile comfort. This idea has been confirmed in various studies [1–4]. Other papers [5–7] focus on the pressure clothes exert on a human body and the conditions of maintaining their comfort when using them. Research [8–10] addresses the issue of designing various knitted structures by means of yarn level modelling. It provides high accuracy of yarn geometry, but significantly increases the time required for calculus [11, 12]. Depending on the algorithms and the purpose of physical process modelling, knitwear can be represented as an orthotropic shell of certain thickness, with specified parameters of elasticity, hygroscopicity, heat conductivity, stiffness etc. In a ready-made product, the level of indicators that affect the comfort of clothes in the process of wearing is predominantly determined by the properties of raw materials they are made of and their knitted structure. Furthermore, the latter is predetermined by the design of the product and the compliance of its size with body measurements. Circumference measurements depend on the position of a human body and the dynamics of its movements [13]. When used, the knitted garment is in a deformed state (especially if the clothing is tight fitted). Thus, the indicators of the above-mentioned properties differ significantly from the ones that refer to not deformed ones. The issues of knitted fabric deformation mechanism and fabric deformation modelling by means of computer tools were studied [14–19].

One of the most popular weft-knitted structures is a rib structure which provides high elasticity without creating any excessive compression. The surface of rib stitch structures possesses certain peculiarities and requires using special algorithms for the creation of macro-models of some parts of knitted products comprising rib structures.

2 Methodology

Within the apparel modelling system, the scale of modelling and corresponding fabric structure idealisation depends on the purpose of its design and input data availability as well as software and hardware tools. It is important to choose appropriate assumptions and idealisations, as well as numerical homogenisation methods. Within the systems of three-dimensional modelling and simulation, knitwear can be represented as an orthotropic textile shell with given thickness. In this case, the product, e.g. a sock, can be presented in the shape of a 3D model as shown in Figure 1.

Figure 1: 3D model of sock represented as shell with homogenised properties within system of three-dimensional modelling

The basic knitted structure element is a loop intermeshed with the loops of the previous and subsequent courses. Furthermore, in the case of 2 × 2, 3 × 3, 4 × 4 and other rib stitch patterns, adjacent knit and purl stitches of the same course can change their mutual position; plain columns width-wise curling can exist as well. As for mechanical characteristics, it is necessary to mention that, depending on the rib stitch pattern and yarn properties, rib stitch structures can have variable levels of stretchability. To represent the physical and mechanical properties of rib stitch structures in macro-models more precisely and to design the mid-surface of tubular rib-knitted shells, the mathematical tool of Bezier curves and ruled surfaces can be used.

2.1 Rib stitch course-wise cross-section

The study of geometric transformations that occur in the process of course-wise stretching of rib-knitted structures [20–22] proved that the change in the configuration and position of separate elements within such a structure is irregular. In the course of stretching, some different processes occur: decreasing of width-wise curling, mutual shifting of adjacent knit and purl stitches, reduction of the curvature of the loop feet and loop heads, pulling the yarn from the loop legs to the loop feet, stretching of the yarn. To study the nature of a thread redistribution within the structure of knitwear, the authors of papers [20–22] used the following notions: the ribbing pattern unit width in mm (*Wru*), the width of the projection of a convex part of a rib stitch pattern on the fabric plane (*C*) and the width of the projection of a visible segment of its concave part on the fabric plane (*S*), as shown in Figure 2. If we divide the process of stretching of knitwear in the course-wise direction into *n* discrete states T_m, where *m* is the number of a given state, we can say that $0 \leq m \leq f$, where 0 is the index of a free state particular to a knitted fabric before applying tensile forces and *f* is the index of the state of maximum tension that is reached by a sample before its destruction. Therefore, the above-mentioned geometric characteristics defined for T_m state can be noted as Wru_m, C_m and S_m (cf. Figure 2).

The cross-section of a 2 × 2 rib-knitted structure during the stretching process can be schematically represented as shown in Figure 3. The relative position of the loops before the process of stretching is shown in Figure 3a, while the change in the relative position of loops during the process of stretching (cf. Figures 3a and 3b) until they gain the state of T_f ($m = f$) is shown in Figure 3d.

Owing to their intrinsic elastic properties, rib stitch structures can often be used to design sock cuffs, necklines, waistlines, borders on sweaters etc.

2.2 Geometric approximation

In recent researches, different approaches are used for textile clothes simulation [23]. The most commonly used are mesoscale modelling [10–12] and macro-level garment simulation [24, 25]. However,

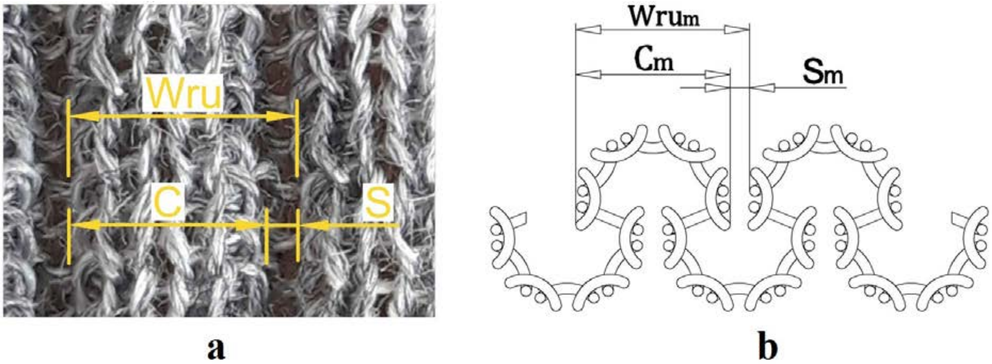

Figure 2: Parts of ribbed patterns within rib stitch structures

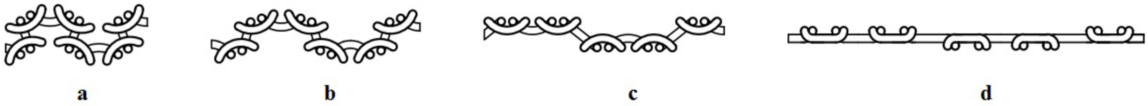

Figure 3: Transformation of knitted fabric elements of 2 × 2 rib structure in process of uniaxial course-wise stretching

according to the authors' knowledge, there is no published work dedicated to macro-modelling of rib-knitted garment parts. The body parts covered with a tubular rib-knitted garment or its segments can be approximated by a set of conical surfaces, e.g. to provide a mathematical analysis of a ribbed sock cuff, it is possible to approximate the leg surface with a frustum (cf. Figure 4b) with the radii of bases R_{s1} and R_{s2}, the perimeters of which correspond to the leg girths in sections 1 and 2, respectively (cf. Figure 4a).

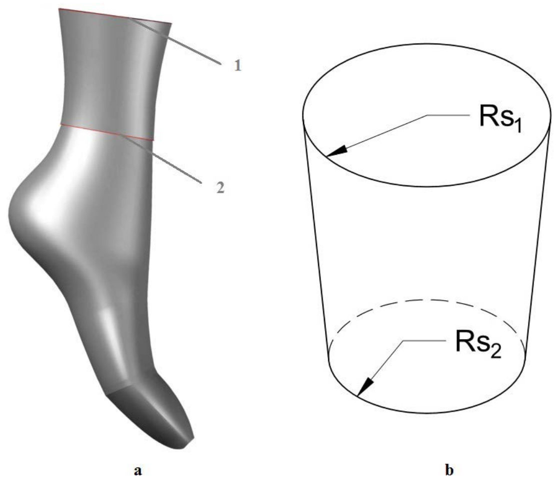

Figure 4: Simplification of shin surface shape with frustum with equivalent base circumferences

3 Results and discussion

In general, if a tubular shell made of an even rib stitch pattern knit is put onto a conical surface, the knitted structure may undergo various levels of stretching in the course-wise direction. In case the tubular rib-knitted garment was produced without changing the number of working needles and stitch density, the number of loops in one course and the loop length do not change.

3.1 Stretching geometry

When the number of rib stitch patterns in one circular course is denoted as N_{ru} and the perimeter of a ribbed tube in a free state as Q_0 (mm), then the pattern width in a free state Wru_0 (mm) can be determined with equation 1:

$$W_{ru_0} = \frac{Q_0}{N_{ru}} \tag{1}$$

If putting a tube with Q_0 perimeter onto a conical surface as shown in Figure 5, three cross-sections with R_1, R_2 and R_3 radii, and Q_1, Q_2 and Q_3 perimeters, respectively, can be schematically represented by three discrete tensile states T_1, T_2 and T_3 as shown in Figure 6. The number of stitches remains unchanged. In the case of transition from T_1 to T_3, the relative elongation increases and the fabric thickness M_m decreases. The pattern width in T_1, T_2 and T_3 can be determined by using equations 2–4.

$$W_{ru_1} = \frac{Q_1}{N_{ru}} \tag{2}$$

$$W_{ru_2} = \frac{Q_2}{N_{ru}} \tag{3}$$

$$W_{ru_3} = \frac{Q_3}{N} \tag{4}$$

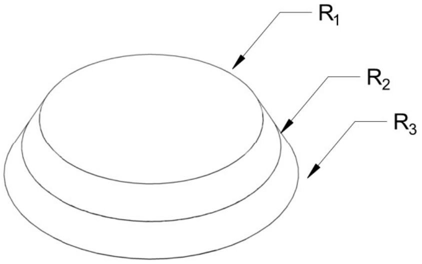

Figure 5: Conical surface with radii of cross-sections R_1, R_2, R_3

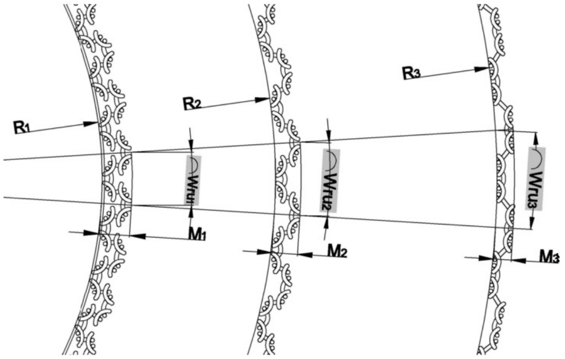

Figure 6: Transformation of knitted fabric elements in case of conical surface wrapped with tube

The correlation of Wru_m, C_m and S_m values for each state of tension depends on many factors and is currently determined experimentally [20–22]. Figure 7 presents macro-models of three stretching states of a sample of 2 × 2 rib structure made of PAN yarn of linear density 32 × 2 tex reproduced according to experimental data as described in [21].

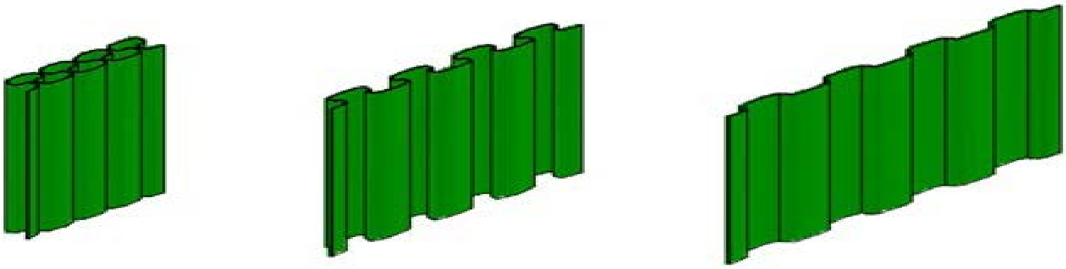

Figure 7: Three states of tension of rib stitch structure sample represented in macro-models

If a ribbed tube is put onto a cylindrical or conical surface, the following algorithm can be used to describe the mid-surface.

3.2 Set of Bezier curves for one repeated unit mid-surface segment

If we assume that 2 × 2 rib stitch structure is wrapped around a cylinder with the perimeter Q_m, where $Q_m \geq Q_0$, then the relative elongation Δl_m (%), can be calculated according to equation 5:

$$\Delta l_m = 100 \times \frac{(Q_m - Q_0)}{Q_0} \tag{5}$$

Figure 8 represents a course-wise cross-section of a repeated pattern unit of a rib-knitted fabric wrapping a cylinder of radius R_m. The control points P_0, P_1, P_{15} and P_{16} belong to the circle line with the radius $R_{m}\_1 = R_m + D_c / 2$, where D_c is a yarn diameter. Then, the control points P_3, P_4, P_5, P_{11}, P_{12}, P_{13} are located on the circle line with the radius $R_{mc} = R_m + M_m / 2$, where M_m is the thickness of the fabric, which corresponds to a given state of stretching. Points P_7, P_8 and P_9 are located on the circle line with the radius $R_{m}\_2 = R_{m}\_1 + M_m - D_c / 2$.

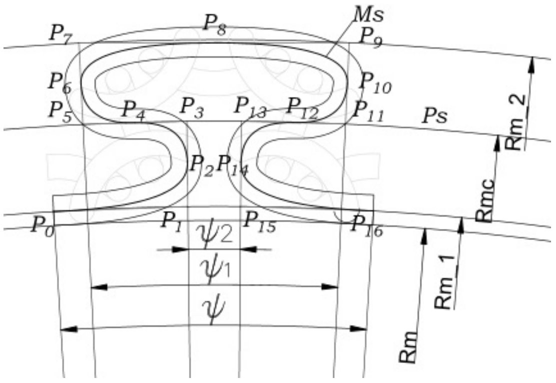

Figure 8: Location of control points of set of quadratic splines for description of 2 × 2 rib-knitted structures mid-surface

$$\psi = \frac{Wru_m \cdot 180}{\pi \cdot R_{mc}} \tag{6}$$

$$\psi_1 = \frac{(C_m - Dc) \cdot 180}{\pi \cdot R_{mc}} \tag{7}$$

$$\psi_2 = \frac{(S_m + Dc) \cdot 180}{\pi \cdot R_{mc}} \tag{8}$$

3.3 Mid-surface geometry description

The ruled surface with guide curves described as quadratic Bezier curves can be used to describe the mid-surface of rib-knitted shells (marked as Ms in Figure 8) pulled over the cone base. The radius vector of the ruled surface $r(u, v)$ (cf. Figure 9) can be described as equation 9:

$$r(u,v) = r_1(u)(1 - v) + r_2(u)v \tag{9}$$

where $0 \leq v \leq 1$ is a point on the generating line, and $r_1(u)$, $r_2(u)$ are quadratic Bezier curves.

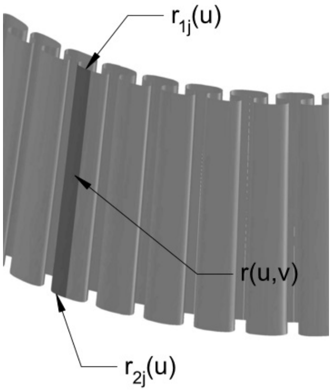

Figure 9: Building of ruled surface fragment upon Bezier curves

Curve lines $r_1(u)$ and $r_2(u)$ are represented as a combination of Bezier curves (equation 10):

$$r_i(u) = \{r_{i0}(u), r_{i1}(u), \dots r_{in}(u)\}, \tag{10}$$

where $r_{ij}(u)$ is a quadratic Bezier curve.

In order to provide the geometric description of a rib stitch pattern (cf. Figure 6), eight quadratic Bezier curves are used. In such a case, a parametric equation of the elementary curve can be presented as follows (equation 11).

$$r_{ij}(u) = P_{i,k}(1-u)^2 + 2 \cdot P_{i,k+1}(1-u) \cdot u + P_{i,k+2}u^2 \tag{11}$$

where k = 0 ... 14 corresponds to the aggregate number of control vertices that determine the directions of tangents for all elementary curves. The combination of elementary curves represents the central line of a rib stitch pattern *Ms* (cf. Figure 8). To increase smoothness between adjoining quadratic Bezier curves, it is necessary that the last point of the first segment and the first point of the second segment coincide as shown in Figure 10. Therefore, the equation can be written as (equation 12):

$$r^{(1)}(1) = r^{(2)}(0) \tag{12}$$

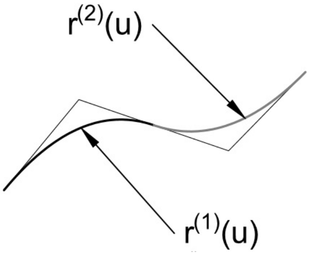

Figure 10: Ensuring smooth connection between adjoining Bezier curves

In addition, the joint segment must have a continuous inclination at the connection point (equation 13):

$$r^{(1)}(1) = \alpha_1 T; r^{(2)}(0) = \alpha_2 T, \tag{13}$$

where T is a unit vector of a common tangent, and α_1, α_2 are scalar constants that influence the completeness of a segment. It can be proved by the example (cf. Figure 8):

$$r^{(1)}(u) = P_0(1-u)^2 + 2P_1(1-u) \cdot u + P_2u^2 \tag{14}$$

$$r^{(2)}(u) = P_2(1-u)^2 + 2P_3(1-u) \cdot u + P_4u^2 \tag{15}$$

$$r^{(1)}(1) = P_2; r^{(2)}(0) = P_2; \tag{16}$$

The first condition is considered. For the continuity of a tangent tilt,

$$r'^{(1)}(1) = 2(P_2 - P_1); r'^{(2)}(0) = 2(P_3 - P_2); \tag{17}$$

the unit vector of a common tangent can be calculated as follows:

$$T = \frac{2(P_2 - P_1)}{\alpha_1} = \frac{2(P_3 - P_2)}{\alpha_2} \tag{18}$$

where α_1 andα_2 are tangent vector lengths.

Therefore, the equation for the segment of a cone surface can be represented with the following formula (equation 19):

$$\begin{aligned} r(u,v) = {} & \left[P_{1,k}(1-u)^2 + 2P_{1,k+1}(1-u)u + P_{1,k+2}u^2\right] \cdot \\ & \cdot (1-v) + \begin{bmatrix} P_{2,k}(1-u)^2 + 2P_{2,k+1}(1-u)u \\ +P_{2,k+2}u^2 \end{bmatrix} \cdot v \end{aligned}, \tag{19}$$

where $0 \le u, v \le 1$.

3.4 Software development

The above proposed mathematical calculations aimed at the geometric description of the mid-surface of rib-knitted shells were installed into the LastikTube program. The latter helps improving the process of designing rib-knitted structure tubular garment parts (cf. Figure 11).

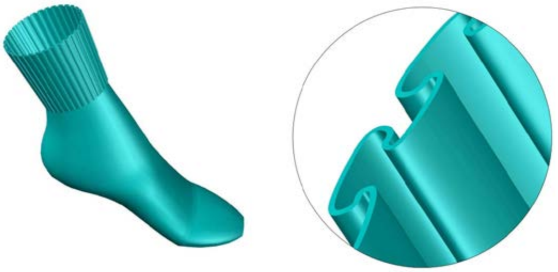

Figure 11: Macro-model of sock, designed as elastic shell, put upon surface approximated by shape of truncated cone

The program contains a database, created during experimental studies, which allows determining the relationship between the geometric characteristics of the surface, e.g. width of Wru pattern, and the widths of its structural parts, i.e. *C* convex and a visible part of a concave area *S* of the pattern unit, created on the base of the analysis of rib knits of various raw materials and pattern numbers.

4 Conclusion

Modelling the physical and mechanical knitwear behaviour in the program environment is one of the most promising ways to increase the usability and functionality of knitwear. During the study, the assumption was made that certain parts of knitwear made by even rib stitch patterns, e.g. 2 × 2, 3 × 3 etc., can be described as thin-walled elastic shells, the middle surface of which is a linear surface created upon a set of Bezier curves located along the contours of truncated cone bases. The software, developed in the course of the research, was used to broaden the capability of computer aided design of knitwear, including the macro-modelling of ribbed tubular garments. 3D models, generated by means of the program, can be used for the assessment of thermophysiological comfort.

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