Virginija Daukantiene, Laima Papreckiene*, Matas Gutauskas

Kaunas University of Technology, Faculty of Design and Technologies, Department of Apparel and Polymer Products Technology
Studentu 56, LT-3031 Kaunas, Lithuania
Tel. +370-7-30 02 05, Fax. +370-7-35 39 89

*** Kaunas University of Technology, Faculty of Fundamental Science, Department of Mathematical Research in Systems**
Studentu 50, 3031 Kaunas, Lithuania
Tel. +370-7-30 03 34

Simulation and Application of the Behaviour of a Textile Fabric while Pulling It Through a Round Hole

Abstract
In this article, we analyse the behaviour of woven and knitted fabrics while pulling a disc-shaped specimen through a round hole of an experimental stand. Some mathematical simulation models have been formed for this complicated process of textile deformation. The results of comparative investigations into six types of textile specimen are presented as a set of geometrical measurements made at different stages of the experiment. The analysis of computational and experimental results shows the sufficient precision of Cassini oval and shortened epicycloid curves for modelling the process. Conditions are identified for applying the method of pulling the textile specimen through the round hole for measuring the parameters of textile anisotropy, textile hand and other mechanical properties.

Key words: *textile hand, pulling textile disc through round hole, textile specimen geometry, anisotropy, mathematical models.*

Introduction

The scientific research works presented in various countries in the recent show the growing interest in experimental investigation of the behaviour of a given textile specimen when pulled through a round hole [1-7]. The research results have led to the creation of several new experimental devices (the JTV-Griff-Tester and the KTU-Griff-Tester), which were designed for the instrumental measurement of textile hand [6,9,13]. It is assumed that the scope of this type of textile investigations can be expanded by measuring the mechanical parameters during the process of pulling a disc-shaped specimen through the round hole of the stand. This method could simplify, quicken and make cheaper the measurement of several mechanical parameters such as anisotropy, and replace the previously used uniaxial strip tension test.

The method of pulling through the hole is applied in several versions. One of the most reliable and generally applied is the method of placing the specimen between parallel plates and pulling it through a central hole made in one of them. During the experiment (Figure 1) the specimen takes on the form of a wrinkled cone under the bottom plate, and a wavy thin-surfaced shape between the bottom plate and the supporting plate.

The appearance of the wavy surface and its contour is determined by the properties of the textile specimen. The specimen cut from woven fabrics obtains a 'four-leaf clover' shape, and the knitted fabric takes on an oval form. These shapes become better defined if the anisotropy coefficient of the fabrics increases and if there is a greater difference in extension rate in the directions of the main axis of the fabrics tested. As fabrics have the greatest mobility towards the direction axis, which forms a 45° angle in respect to the weft yarn direction, the stiff parts of the specimen (the warp and weft) make the fastest movement towards the centre during the experiment.The movement along the diagonal axis is slowed down by friction forces; thus the specimen is extended and forms each of the four leaves of the clover shape. The most clearly defined shape of the four-leaf clover is formed from the fabrics with the most mobile structure. If the specimen is made of very dense fabrics or covered with polymer film, it assumes the form of a wrinkled quadrangle (parallelogram) with rounded corners.

The specimen cut from knitted fabrics has the perpendicular axis of the highest mobility in the direction of rows and the lowest mobility in the direction of columns. Thus its shape during the experiment forms the contour which changes from a circle to an ellipse, which tends to show a contour break towards the stiff column direction. This depends on the anisotropy coefficient of the fabrics K_a. The change in shape of the experimental specimen is especially evident when K_a>10.

Goal

The goal of the research was to present a method for the comparative evaluation of the behaviour of different types of textile fabrics during the process of pulling the disc-shaped specimen through the round central hole of the experimental stand bottom plate. The main steps taken to achieve this goal were as follows: to investigate mathematical models for simulating the behaviour under discussion, to define the parameters and scope of applying the mathematical models, to compare the measurements of disc geometrical transformations to the measurements of uniaxial deformation of woven and knitted fabrics at different direction angles, to show the advantages of the method presented for testing and simulating the behaviour of a given textile, and measuring and predicting parameters during fabric exploitation.

Methodology

The experimental part of the research was performed using the KTU-Griff-Tester device with the following parameters: radius of the specimen R=56.5 mm (area of the specimen - 100 cm^2), the holes made in the supporting plates had radiuses r of 7.5, 10, 12.5 and 15 mm. The distance h between the supporting plate and the bottom plate can be adjusted with the precision of 0.05 mm and is chosen according to the thickness of the fabrics δ, its peculiarities of jamming in the hole of the bottom plate and between the bottom and the supporting plate [7]. The specimen is pulled through the hole of the bottom plate using a spherical punch with the radius

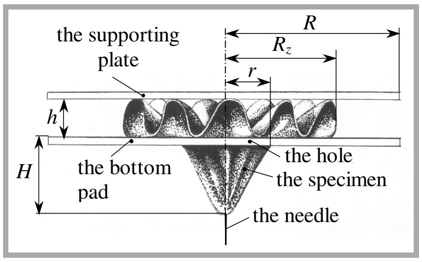

Figure 1. Principal scheme of textile hand evaluation in pulling process.

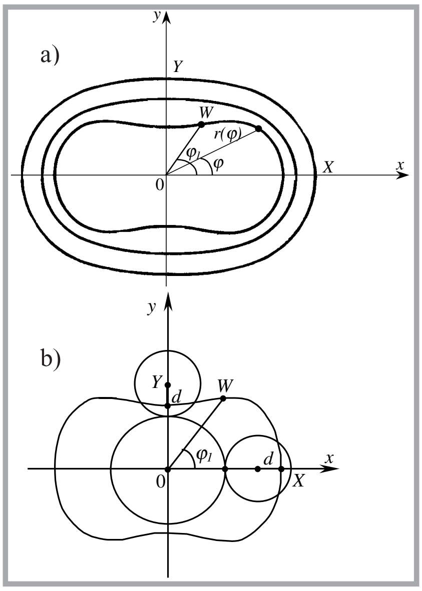

Figure 2. Cassini ovals (a) and shortened epicycloid, where the radiuses of the circles are 2a and a; (b) 0<d<a.

of 5 mm, and the hole in the bottom plate is processed by rounding its edges to a radius of 1 mm.

Six sample fabrics were investigated (Table 1), two woven and four knitted, which differed in structure, thickness and coefficient of anisotropy. The behaviour of the fabrics was investigated by two tests: pulling them through the hole made in a transparent bottom plate (organic glass), and stretching stripes of the same types of fabrics (uniaxial tension test) which were cut in directions differently oriented in respect to the fabric course/warp.

The behaviour of each specimen was recorded with the help of a digital camera during the 4-6 deformation stages. The images captured were used to measure the distance from the edge of the specimen R_z (Figure 1) to the centre of the specimen at intervals of 15 degrees. The specimens for the uniaxial tension test were cut from the identical fabrics by cutting strips (of 20 mm width) which were oriented at the same direction angles as in the first test. The constant tension load, similar to that during exploitation, was used to deform the fabric strips. The differences between the linear deformations of the disc and the strip-shaped specimen were used to identify the similarities and differences of the tests.

Mathematical Models

It is assumed that before the experiment, the Cartesian x, y, and polar r, φ co-ordinates will be set on the bottom plate plane. The original co-ordinate point 0 is set in the centre of the specimen, and the original polar axis (0x axis) takes the weft direction of the woven fabrics or the wale direction of the knitted fabrics.

1. As the specimen of ***knitted fabric*** is pulled through the hole, its contour changes from that of a circle to a wavy spatial curve. The projection of the curve on the bottom plate plane is similar to the ellipse in the beginning of the experiment; then it narrows, becomes incurved and finally assumes the '∞' shape (Figure 2a). These curves represent certain cases of Cassini ovals, known in the scientific literature [10-12]

$$r^2 = c^2 \cos 2\varphi + \sqrt{c^4 \cos^2 2\varphi + a^4 - c^4} \quad (1)$$

where the relationships of the parameters *a* and *c* are firstly

$a \geq c\sqrt{2}$, then $c < a < c\sqrt{2}$

and finally *a=c*.

Though the reference sources present quite a lot of information regarding these curves, our special interest lies in the polar co-ordinates of the curve's inclination points. In the I quarter, the co-ordinate φ_1 of the inclination point W is calculated from the equation:

$$\cos 2\varphi_1 = -\sqrt{\frac{a^4 - c^4}{3c^4}} \quad (2)$$

The other type of curves of similar shape are well known in the academic literature of mathematics. One of them is called an epicycloid, which is formed as trajectory of the point belonging to the circle contour (radius *a*) while it rolls along the outer side of the other circle (radius *2a*). The other has a similar shape and is called a shortened epicycloid, which is formed by the internal point of the circle (radius a, the distance from the centre of the circle

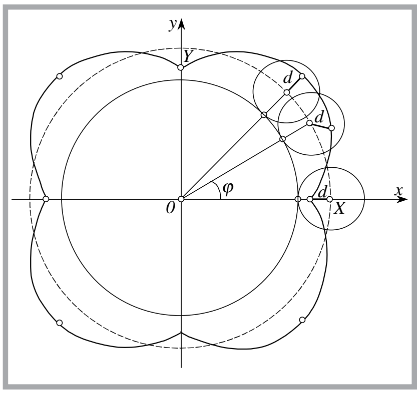

Figure 3. The formation scheme of the shortened epicycloid, when the radiuses of the circles are 4a and a.

d, d<a), while it rolls along the outer side of the other circle (radius *2a*). Thus the epicycloid is formed when *d=a*.

The parametral equations for the shortened epicycloid and the epicycloid are the equations (3) and the equations (4) (for expression the function in the polar co-ordinates); when *d=a*, this relative can be written as

$$r(\varphi) = a\sqrt{10 + 6\cos 2\varphi} \quad (5)$$

The polar co-ordinate φ of the inclination point *W* (I quarter) is calculated from the equation:

$$\cos 2\varphi = -\frac{a^2 + 3d^2}{4d} \quad (6)$$

When $|a| > 5|d|$ and $|a| < |d|$ the inclination points are missing.

2. As the specimen of ***woven fabric*** is pulled through the hole, its contour is deformed from the shape of a circle to the specific curve presented in Figure 3. Its projection on the bottom plate plane can be described using the same mathematical equations (3), where *d*<0, as presented by (7).

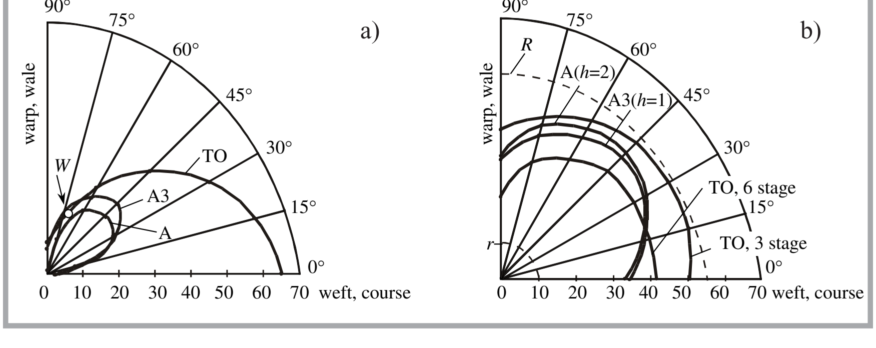

Figure 4. The distribution of the linear deformations during uniaxial tension, at P=1.2 N and the dimensions of strip working area of 100×20 mm (a) and while pulling the disc-shaped specimen through the hole of the stand's bottom plate, when R=56.5 mm, r=10 mm, ρ=5 mm, h≅3δ mm (b).

The distance from the points of the shortened epicycloids to the centre *0* is $R_z=r(\varphi)$

$$r(\varphi)=\sqrt{x^2+y^2}=\sqrt{25a^2-10ad\cos 4\varphi+d^2} \quad (8)$$
$$r(\varphi)=a\sqrt{26-10\cos 4\varphi}$$

when $d=a$, the co-ordinate φ of the inclination point *W* is calculated from formula (9)

$$\cos 4\varphi=-\frac{a^2+5d^2}{6ad} \quad (9)$$

While analysing the experimental results, the feasibility of applying other mathematical models was examined as well, namely Buto Lemniscate, Lame and Persay curves, and four-leaf flowers [12]. The Cassini ovals and shortened epicycloids were evaluated as being most suitable for further investigations, because the results of applying these models had the highest reliability, especially in the initial stages of deformation.

Results and Discussion

A small load P=1.2 N was applied to the stripes of woven fabrics A and A3, as well as to the knitted fabrics TO. During the first minute, they reached different extension rates (Figure 4a). The largest extension of the woven fabrics was reached for the stripes cut at the direction of 45°, and the smallest extension was measured for the stripes cut in warp (A) or weft (A3) directions. The curves were drawn by linking the extension points measured in all sectors. The curves drawn for woven fabrics are similar to ovals, oriented towards the 45° direction axis. The knitted fabrics TO reached the maximum deformation in the course direction and the minimum deformation towards the wale direction. The investigation showed that the shape of the linear deformation curves depends on the stripe cutting direction axis, and it has an inclination point, if the cutting direction approaches the course axis (indicated for the strips, cut at 75° in respect to the fabric course direction).

While pulling the disc-shape specimen through the hole of the bottom plate, the linear deformation curves resemble the curves of stripe deformation, as shown for one sector of the circle (90°) (Figure 4a). The displacements R_z of the disc-shaped specimen's outer contour were measured after pulling it through the hole of the stand. The largest displacements were obtained for the woven fabric warp and weft yarns. The smallest displacement of the specimen outer contour was in the 45° direction, and the intermediate values of R_z were in the 15°-30° and 60°-75°directions. The differences between the displacements of the specimen's outer contour in intermediate fabric directions are insignificant. So, the 'four-leaved clover', the axles of which are located at 45° angles in respect to the 0x and 0y axles, is formed from the woven fabric specimen (while pulling of the disc shaped specimen through the central hole). The curves of the knitted fabric TO's linear deformations for the same sector of the circle are similar in both deformation cases, while pulling of rounded specimen through the hole or after the uniaxial strip tension (Figure 4). The displacements of the specimen outer contour are smaller after pulling the specimen through the hole compared to those obtained after the uniaxial deformation. The reason for this was the different mode of spatial deformation. The displacements of the adjacent points of the specimen are limited while pulling it through the stand hole. The shape of the single sector of the specimen cut from the knitted fabric TO is similar to that of the one-quarter of incurved oval, and the depth (size) depends on the level of the specimen deformation.

The experimental results obtained after pulling the rounded specimens cut from the woven or knitted fabric through the hole (Figures 5 and 6) were compared to those calculated by using the mathematical models. The parameters *a* and *c* of the (1) Cassini oval equation were calculated using the measured parameters OX (φ=0°) and OY (φ=90°) (Figure 2a):

$$\begin{cases} a^2+c^2=OX^2, \\ a^2-c^2=OY^2 \end{cases} \quad (10)$$

After the substitution of the obtained a^2 and c^2 values into equation (1), we calculated $r(\varphi)$, when φ=15°; 30°; 45°; 60°; 75° and compared them to the measured values (Table 1). The differences between the measured and calculated parameters were evaluated by using the equation:

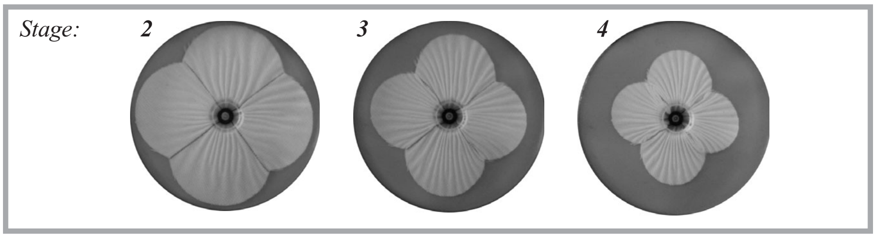

Figure 5. *The projections of the specimen from the woven fabric A3 in the plane of the stand's bottom plate at the different deformation stages; stage: 2 (H=20 mm), 3 (H=30 mm) 4 (H=40 mm).*

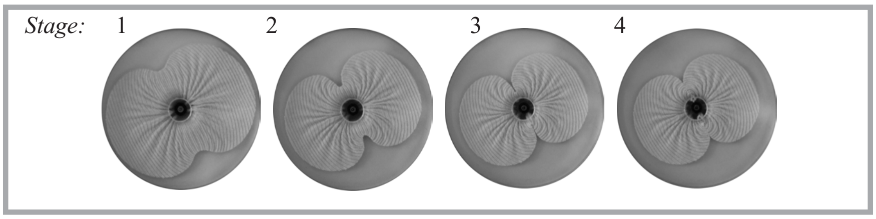

Figure 6. *The projections of the specimen from the knitted fabric V in the plane of the stand»s bottom plate at the different deformation stages; 1 (H=10 mm), 2 (H=20 mm), 3 (H=30 mm) 4 (H=40 mm).*

Table 1. *Characteristics of textile fabrics. Note: $K_a=\varepsilon_s/\varepsilon_i$, where ε_s - linear deformation of the specimen in weft/wale direction, ε_i - the same in warp/course direction.*

Fabric	Symbol	Fabric content	Fabric structure	Thickness δ, mm	Specimen weight, g	Coefficient of anisotropy K_a
Woven fabric for suit	A	Wool Polyester	Hopsack	0.63	2.52	2.7
Woven fabric for shirt	A3	Polyester (warp) Viscose (weft)	Hopsack	0.39	1.24	0.2
Knitted fabric	T2	50% cotton 50% wiscose	Interlock 1×1 rib.	1.00	2.60	3.1
Knitted fabric	TO	100% cotton	Interlock 1×1 rib.	0.89	2.47	7.3
Knitted fabric	R	100% cotton	Interlock 1×1 rib.	0.87	2.14	6.5
Knitted fabric	V	100% cotton	Interlock 2×2 rib.	0.79	1.43	12.5

$$\Delta = r_{measured}(\varphi) - r_{computed}(\varphi) \qquad (11)$$

and are presented in Table 4.

When $a < c\sqrt{2}$, the polar coordinate φ_1 of the inclination point *W* of the curve (Cassini oval) for the Ist one-quarter was calculated from equation (2). We also used the same measured parameters to calculate the parameters *a* and *d* of the shortened epicycloid (4) equation: when φ=0°, *3a+d=OX*, and when φ=90°, *3a-d=OY*.

After the solution of the equation system

$$\begin{cases} 3a + d = OX, \\ 3a - d = OY, \end{cases} \qquad (12)$$

and substitution of *3a* and *d* values into equation (4), the *r(φ)* values were determined. So later, the *Δ* values were obtained using equation (11) and the co-ordinates of the inclination point of curve were calculated using equation (6).

After comparison of the *Δ* values obtained for both cases, it was determined which of the mathematical curves - the Cassini oval or the shortened epicycloid - would be better for simulating the shape of the outer contour projection of the deformed specimen.

The results presented in Tables 2 and 3 prove that after the initial stages of specimen deformation (3rd-4th stages) the projection of the specimen's outer contour obtains a non-incurved oval shape (with the bend point *W*). The later increase of deformation (5th-6th stages) forms the inclination of the oval near the y axis, and the distance OY between the inclination point of inclination *W* and the centre *0* is variable. After the performed calculations, it was determined that the outer contour of the deformed specimen obtains the shape of the non-incurved oval.

The theoretical investigations concerning the behaviour of the specimen cut from the woven fabrics A and A3 while being pulled through the central hole were performed using equation (8). When φ=0°, *5a-d=OX*, and when φ=45°, *5a+d=OY*. The values of the *a* and *d* parameters were calculated using the equation system

$$\begin{cases} 5a - d = OX, \\ 5a + d = OY \end{cases} \qquad (13)$$

After substituting the calculated values of the *a* and *d* parameters into equation (8), the values *r*(15°), *r*(30°), *r*(60°), *r*(75°) were obtained and the differences *Δ* were calculated. The next step was to calculate the values of the polar coordinates of the curve's inclination point using equation (9). All calculated parameters are presented in Table 4.

The investigations presented concerning the behaviour of woven and knitted fabric while pulling specimens of them through the central hole of the stand have proved that the method of pulling them through the hole can more realistically simulate the wearing conditions of textile garments than the standard uniaxial strip tension test. This statement can be substantiated on the basis of the uniaxial deformation of strip-shaped specimens cut in the diagonal fabric directions. During deformation of the strip-shaped specimens cut from textile fabric in 45±15° angles, the same fabric yarns fixed in both clamps of the tensile machine are missing. So, the deformation of such strip can simulate only the shear processes; it is dissimilar from the fabric deformation in the weft/wale and warp/course directions (0° and 90°). While pulling the disc shaped specimen through the hole of the stand, the strains in the specimen area are distributed differently in comparison to those arising during the uniaxial strip tension because of the correlation of all the specimen directions. Notwithstanding this, the method of pulling through a hole is classed together with the tests of the biaxial deformation, but some similarities exist between the deformation of the strip-shaped specimens and the deformation of the disc-shaped specimens. The first similarity is the remaining directions of maximum and

$$\begin{cases} x = (2a+a)\cos\varphi + d\cos\dfrac{2a+a}{a}\varphi; \\ y = (2a+a)\sin\varphi + d\sin\dfrac{2a+a}{a}\varphi; \end{cases} \qquad 0 \le \varphi \le 2\pi, \qquad 3)$$

$$r(\varphi) = \sqrt{(2a+a)^2 + 2(2a+a)d\cos\frac{2a}{a}\varphi + d^2}, \text{ or} \qquad 4)$$

$$r(\varphi) = \sqrt{9a^2 + 6ad\cos 2\varphi + d^2};$$

$$\begin{cases} x = (4a+a)\cos\varphi - d\cos\dfrac{4a+a}{a}\varphi; \\ y = (4a+a)\sin\varphi - d\sin\dfrac{2a+a}{a}\varphi; \end{cases} \quad \text{or} \quad \begin{cases} x = 5a\cos\varphi - d\cos 5\varphi; \\ y = 5a\sin\varphi - d\sin 5\varphi. \end{cases} \qquad 7)$$

Equations 3, 4, and 7.

Table 2. *The measured values of the displacements R_z of specimen outer contour points at the initial deformation stages. Note: The stages of the specimen deformation were numbered in accordance with the motion of the pulling punch H (every 10 mm): 1st stage, when H=10 mm, 2nd stage - H=20 mm, 3rd stage - H=30 mm, 4th stage - H=40 mm, 5th stage - H=50 mm, 6th stage - H=60 mm.*

Fabric symbol (Table 1)	Deformation stage	R_z, mm						
		0°	15°	30°	45°	60°	75°	90°
A	2	33.0	36.0	41.5	44.0	42.5	36.5	32.0
A3	2	33.5	39.5	45.0	47.0	46.0	41.5	33.0
T2	2	50.0	50.0	49.2	47.5	44.9	41.5	40.7
	3	46.7	45.0	44.2	43.3	39.2	33.3	32.1
TO	3	50.5	52.0	51.5	51.0	48.0	44.0	40.0
	6	41.5	41.0	41.0	40.0	36.0	31.0	22.0
R	2	51.7	50.8	50.0	46.6	42.4	36.4	35.2
	3	47.1	46.3	45.5	41.3	35.5	28.1	24.8
V	2	50.6	50.4	48.8	47.1	43.0	36.4	29.0
	3	45.0	44.2	43.3	41.7	36.7	29.2	17.5

Table 3*. The measured values of the displacements R_z of the specimen from the knitted fabric TO's outer contour points at the 3rd-6th deformation stages and the coordinates of the inclination point W of curve.*

Deformation stage	R_z, mm, when φ							Coordinate φ_1 of the inclination point W
	0°	15°	30°	45°	60°	75°	90°	
3	50.5	52.0	51.5	51.0	48.0	44.0	40.0	are missing
4	46.0	47.2	46.2	46.5	44.0	37.0	32.0	are missing
5	42.5	42.0	42.0	40.5	37.0	31.5	24.0	81°36'
6	41.5	41.0	41.0	40.0	36.0	31.0	22.0	74°11'

Table 4. The values of the difference Δ (error).

Fabric symbol	Deformation stage	Δ, mm							The place of the inclination point
		0°	15°	30°	45°	60°	75°	90°	
CASSINI OVALS									
TO	3	0	2.27	3.84	6.06	5.62	3.38	0	are missing
	6	0	1.06	5.31	9.78	10.42	8.14	0	74°11'
V	2	0	1.51	4.54	8.79	9.85	6.38	0	88°27'
	3	0	1.45	6.87	13.64	15.08	10.78	0	75°45'
R	2	0	0.37	2.97	3.94	3.72	0.32	0	are missing
	3	0	0.99	5.06	7.12	6.62	2.32	0	73°38'
T2	2	0	0.68	1.69	2.39	2.06	0.24	0	are missing
	3	0	-0.58	1.61	4.58	4.00	0.41	0	86°
SHORTENED EPICYCLOIDS									
A	2	0	0.07	0.02	0	0.98	0.43	-1	45°±8°31'
A3	2	0	2.16	0.99	0	1.99	4.16	0.5	45°±6°32'
TO	3	0	2.14	3.41	5.45	5.13	3.21	0	77°29'
	6	0	0.51	3.41	6.79	7.83	7.19	0	82°6'
V	2	0	0.95	2.64	5.86	7.35	5.48	0	78°17'
	3	0	0.50	3.36	7.56	9.57	8.67	0	are missing
R	2	0	0.04	1.89	2.37	2.43	0.14	0	75°1'
	3	0	0.36	2.87	3.66	3.63	1.22	0	82°34'
T2	2	0	0.57	1.39	1.94	1.72	0.11	0	are missing
	3	0	-0.87	0.69	3.23	2.90	0.02	0	75°2'

minimum deformations. In addition, the polar diagrams are also similar (Figure 4): the deformed specimen cut from knitted fabric obtains the shape of an oval with a bend point near the angle of 90°, and the specimen from woven fabric obtains the shape of the 'four-leaf clover', where the smallest displacement of the outer specimen contour R_z is near the angle of 45°. The third similarity was the close resemblance between the coefficient of anisotropy K_a determined experimentally by the uniaxial tension method (Table 1) and the computed parameter d, which was obtained after the test of pulling through the hole. This is particularly relevant to knitted textile materials (Table 5).

Some evident specimen transformations were observed while pulling the disc through the central hole. The most conspicuous specimen transformations were noted when the specimen outer contour approached the edge of the stand hole (R_z approximates r) (Figure 1).

The analysis of the specimen images captured at different specimen deformation stages have shown that the projections of the woven fabric specimen's outer contour can be mathematically simulated by the equation of the shortened epicycloid, and those of knitted fabric by the equations of Cassini ovals or of the shortened epicycloid. The precision of the mathematical simulation notably decreases when the outer contour of the specimen nears the edge of the hole, especially after a significant increase in the coefficient of the anisotropy of textile fabric's properties. The simulation of the geometrical shapes of the specimens cut from the knitted fabric V (K_a=12.5) can serve as one example of this phenomenon. In such a case, the typical scheme of the process of pulling though the hole is missing, when after half of the deformation process the stiffer system of the knitted fabric (the course axis of fabric) enters the stand hole.

The investigations presented are important both for solving the problem of the instrumental textile hand evaluation and the simulation of some of the wearing processes of technical textile products (parachutes, sails, filters, functional clothing etc.).

Table 5. Coefficient of anisotropy K_a and the computed d parameter.

Fabric	K_a	d
T2	3.1	4.13
TO	7.3	9.25
R	6.5	8.25
V	12.5	13.75

Conclusions

- The differences between knitted and woven fabric geometrical transformations during the experiment of pulling them through the hole of the test stand were evaluated and compared.
- Simple (i.e. with a small number of parameters) and reliable mathematical models were presented for simulating the behaviour of specimens of disc-shaped fabrics during the process of pulling them through the hole. The best results were achieved by using models of the Cassini oval and the shortened epicycloid, which showed the best reliability in the initial stages of the experiment. When the stiffest part of the specimen approaches the hole's centre, the precision of the model decreases.
- The experiment of pulling the disc through the hole preserves the evidence of the dependence of the qualities of the textile fabrics on the different direction axis. This experiment is simple to perform, provides new information about the behaviour of textile fabrics and can be more widely applied in textile material science.

References

1. Bishop D. P. Fabrics: 'Sensory and Mechanical Properties', Journal of the Textile Institute, ISSN 0040-5167, England, 3(26), 1996, pp. 1-63.
2. Ellis B. C., Garnsworthy R. K.: 'Review of Techniques for the Assessment of Hand', Textile Research Journal, No. 4, 1980, pp. 231-238.
3. Grover G., Sultan M. A., Spivak S. M.: 'A Screening Technique for Fabric Handle', Journal of the Textile Institute, ISSN 0040-5167, England, 3(23), 1993, pp. 486-494.
4. Harlock S. C.: 'A study of the handle characteristics of rib knitted cotton fabrics', International Journal of Clothing Science and Technology. ISSN 0955-6222, 6 (12) 2000, pp. 53-54.
5. Hennrich L., Seidel A., Rieder O.: 'The test of knitted fabric hand', Maschen-Industrie, 7 (1999), pp. 46-47 (in German).
6. Seidel S.: 'The Estimation of Hose Hand by ITV-Griff-Tester', Melliand Textilberichte, ISSN 0341-0781, 6 (2001), pp. 491-493 (in German).
7. Martisiute G., Gutauskas M.: 'New Approach to Evaluation of Textile Fabric Handle', Medžiagotyra (Materials Science), ISSN 1392-1320, Kaunas: Technology, 2001, 3 (7), pp. 186-190.
8. Martisiute G., Gutauskas M.: 'The pulling of knitted fabric membrane through a hole: geometry analysis', Design and Technology of Consumables. Kaunas: Technology, 2001, pp. 78-83 (in Lithuanian).
9. Martisiute G., Gutauskas M.: 'The device for textile hand evaluation', Design and Technology of Consumables. Kaunas: Technology, 2002, pp. 63-66 (in Lithuanian).
10. Vygodsky M. Ja.: Manual of higher mathematics. - Moskva: National press of physical-mathematical literature, 1963.- cc.770, 805. (870 c.) (in Russian).
11. Minuscule Encyclopaedia. Mathematics. - Leipzig: VEB press of Encyclopaedia, 1968. pp. 449-450. (837 p.)
12. Savielov A. A.: Plane curves. - Moskva: National press of physical-mathematical literature, 1960, 293 c. (in Russian).
13. Gutauskas M., Papreckiene L., Strazdiene E.: 'New methods for the objective evaluation of technical textile behaviour', 6 Dresdner Textiltagung 2002, Biofunktionelle Materialien, FIZ Technik Literaturdatenbank, http://www.fiz-technik.de.

Received 29.10.2002 Reviewed 19.03.2003