NEW POSSIBILITY OF OBJECTIVE EVALUATION OF YARN APPEARANCE: PART II

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Abstract:
In this article, the possibility of new objective evaluation of yarn appearance in area employing selected spatial statistical functions is presented. The yarns wound on the boards were used for the experiment. Appearance of standard yarn boards from the standard CSN 80 0704 and real yarn boards with faultless and faulty yarns were converted into grayscale images. Fluctuation in degrees of grayness was evaluated between square fields in the image using statistical function called the area variation curve. In addition, the method was applied to the simulated yarn board appearance generated by the Uster Tester apparatus. Behavior of area variation curves in dependence on the result of visual evaluation of yarn board appearance was discussed. The generated appearances from the Uster Tester device were also evaluated by other statistical function called semivariogram. It was found out that the area variation curve is not a suitable tool for evaluation of yarn board appearance. The semivariogram seems to be a more suitable tool. The paper extends the knowledge on the issue of objective evaluation of yarn appearance and directly follows the author’s work [1].

Keywords:
Yarn appearance, Evaluation, Area variation curve, Semivariogram, Yarn board, Yarn grades

Introduction
This paper is a direct follow-up of the authors’ work [1], where the spatial statistical function called semivariogram was introduced as a possible tool for the objective evaluation of yarn appearance.

Yarn quality is judged according to the achieved values of tested yarn properties that are selected in dependence on yarn utilization. Quality level of the yarns can be assessed using the USTER® STATISTICS [2]. This tool is composed of graphs enabling users to compare their measured results of yarn (silver, roving, fiber) with the corresponding worldwide established fibrous product quality reference values; in the case of yarns, it includes count variation, mass variation, imperfection, hairiness, diameter variation as well as tensile properties.

Yarn count variation, mass and diameter variation, imperfection and hairiness mainly affect the yarn appearance. In practice, the yarn appearance is usually evaluated subjectively by comparing a yarn board of defined winding density with a standard yarn board according to ASTM D 2255-90 [3], or according to standard CSN 80 0704, which is used in the Czech Republic [4]. The evaluation is dependent on the reviewer and their ability to visually compare yarns. The company Lawson-Hemphill in cooperation with the United States Department of Agriculture and Cotton Inc. has developed the automated yarn grading system according to ASTM for several counts [5,6]. This system also known as EIB (Electronic Inspection Board) or YAS (Yarn Analysis System) uses optical digital technology and replaces human inspection grading [6]. The other method simulating the procedure of subjective visual assessment of yarn appearance is introduced in work [7].

Some devices for measuring yarn mass irregularity (e.g. Uster Tester) allow users, among others, to display the appearance of measured yarn wound on the board (yarn taper board), but they do not grade the yarn. Generally, on the yarn board, it is possible to identify the characteristic expression of yarn mass irregularity – the moiré effect (short-term periodical irregularity), stripiness (very long-term periodical irregularity). The non-periodical irregularity of yarn expresses itself in the area (on the board) as unsettled appearance of textile. Furthermore, the appearance of yarns in the area is influenced by other random exposures, which are determined by the structure of yarn mass irregularity, yarn faults, impurities and yarn hairiness. Yarn irregularity can be described by parameters (CV, U, DR), which indicate a level of irregularity, and characteristic functions (a spectrogram, a variance-length curve), which can help in indicating the cause of irregularity in yarn. On the basis of these functions, we can predicate the appearance of future plain textile. In the literature, the interrelation between the course of spectrogram (the periodical irregularity) and the moiré effect as well as the stripiness [8] and between the course of variance-length curve and unsettled appearance of plain textile [9] is mentioned.

Several research works have been carried out to present the objective evaluation of yarn appearance. For example, the work by Kim et al. [10] described a developed quantitative method for grading spun yarn appearance derived from optical yarn diameter measurements. Semnani et al. [11,12] introduced a
method for grading the appearance of various types of yarn using image analysis and artificial neural network. The work by [13], described a new device for evaluating a yarn on the surface as an independent formation. Recently, Liang et al. [14] presented intelligent characterization and evaluation of yarn surface appearance using saliency map analysis, wavelet transform and fuzzy neural network. Another method presented by Rong et al. [15] graded yarns by cluster analysis.

The derived statistical function [16,17] can be used for the objective evaluation of surface unevenness. For the evaluation, both generated images of the appearance of the textile in area (yarn taper board, woven fabrics, knitted fabric), and images of real fabrics or yarn board can be used. Simulated image of the appearance is in grayscale with different levels of gray, the real image of gray textile is converted into grayness degrees. Grayness degrees reflect the unevenness of textile and in the case of yarn, its faults. Thus, surface unevenness of a textile can be converted into the unevenness of color of fabric images. The yarn mass irregularity and yarn faults also present non-uniformity in a color image. The fluctuation of average grayness degrees in the image can be evaluated by means of statistical functions. Essentially, a sample of the flat textile is divided into square fields, where individual properties (grayness degrees) are measured. The so-called area-variation curves can be constructed as a parallel of a variation-length curve. The area variation curve is also used in works [18,19] as a quantitative evaluation of the quality of predicated image of the plain textile. It has been suggested as a new evaluation method of woven fabric unevenness [20]. Surface variability can also be described by other statistical functions, for example the so-called directional semivariograms [17,21,22]. The semivariogram was used for evaluation of the surface variability of woven and nonwoven fabrics [23-25] and it was also applied on evaluating the appearance of standard yarn boards from the standard CSN 80 0704 as well as real yarn boards with faultless and faulty yarn [1].

The new suggested methods for the objective evaluation of yarn appearance are analyzed in this paper. Considering the same yarn count and constant winding density, the appearance of yarn wound on the board is influenced mainly by variations in the yarn diameter, yarn hairiness, number of yarn faults, remains of impurities as well as yarn mass irregularity. We suppose that the appearance of yarn transfers itself into fluctuation in degrees of grayness after digitizing and converting the yarn board to a grayscale image. In the presented work, the variation of degrees of grayness in an obtained image of the yarn board appearance is evaluated using a spatial statistical function called the area variation curve. This method is applied to the same yarn boards (standard and real) as in work [1]. In addition, the simulated appearance of yarn taper boards generated by the Uster Tester IV-SX device is used. The behavior of the constructed area variation curves in dependence on the results of visual evaluation of the yarn board appearance is discussed. For the verification of results described in [1], the appearance of the generated yarn boards is evaluated by semivariograms too. Employing both these functions for the objective evaluation of the yarn board appearance is discussed here.

**Tools for yarn board appearance evaluation**

**Area variation curve**

The area variation curve describes the variability of grayness degrees in dependence on the square field area. It can be expressed as an external or an internal curve. The internal area variation curve records the variation coefficient of grayness degrees inside the square area in dependence on the area of the observed square fields. This curve increases with the growing area of square fields. The external variation curve shows the variability of grayness degrees between the square field areas of an image. The curve slopes down with the growing area of square fields. In this work, we used the external area variation curve which is calculated as:

\[
CVB(A) = \frac{S(A)}{X(A)}
\]

where \(CVB(A)\) is the external variation coefficient of average grayness degrees between the square fields of area \(A\) in the fabric image; \(S(A)\) is the standard deviation of the mean values of grayness degrees in the square fields of area \(A\) included in a fabric image; \(X(A)\) is the mean value from all mean values of grayness degrees in the square fields of area \(A\).

**Semivariogram**

The statistical function semivariogram can be used for evaluating the variability of random field properties. In this case, the yarn board was converted into grayness degrees and divided into square fields like a net. The centers of the fields are the locations \(x\). The average value of grayness degree in the given square field is assigned to location \(x\) \((z(x))\). The semivariogram expresses spatial dissimilarity between the values of grayness degrees at points \(x_i\) and \(x_j\), and its general definition is mentioned in works [23-26]. We used the so-called centered sample semivariogram [22]:

\[
G(lag) = \frac{1}{2N(lag)} \sum_{i=1}^{N(lag)} (z_c(x_i) - z_c(x_i + lag))^2
\]

where \(z_c(x)\) is the centered average grayness degree defined as:

\[
z_c(x) = \frac{\sum_{i=1}^{n(x_i)} z(x_i)}{n(x_i)}
\]

\(N(lag)\) is the number of pairs of observations separated by distance \(lag\) and \(z(x_i)\) is the grayness degree in location \(x_i\).

Four types of semivariograms can be constructed in direction of columns, rows, diagonals and omni-semivariogram as an average of the mentioned three types of semivariogram.
Experimental part

For the experiment we used:

a) Appearance of yarn taper boards and appearances of magnified yarn boards generated by the Uster Tester IV-SX apparatus based on measurements of yarn mass irregularity. These boards are one of the outputs of this device; the magnified yarn board shows a zoomed part of the regular taper board, with a different pitch [27] (for example see Figures 1a and 1b).

b) Real standard yarn boards – (called etalons) from CSN 80 0704 - grade A to F (for example see Figures 2a and 2b).

c) Real yarn boards of two qualities – 100% CO rotor spun yarns of fineness 30 tex without faults and with short-term irregularity caused the moiré effect (see Figures 3a and 3b) were wound on the black board with the same winding by the Planiscop device.

The images of yarn appearance generated by the Uster Tester apparatus were printed and scanned. The real yarn boards were scanned. The scanning resolution was 300 dpi and the obtained images were saved in a non-compressed tiff format. The images were treated in the script “Fabric unevenness” written by Militký, J. (Technical University of Liberec) in programming environment Matlab. The program converts images to grayscale. The area variation curve and semivariograms are the output

Table 1. Short description of yarn used for experiment.

<table>
<thead>
<tr>
<th>Yarn No.</th>
<th>Yarn count T [tex]</th>
<th>CV_m [%]</th>
<th>CV(1m) [%]</th>
<th>CV(3m) [%]</th>
<th>CV(10m) [%]</th>
<th>Thin place -50% [1/km]</th>
<th>Thick place +50% [1/km]</th>
<th>Neps +200% [1/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>18,29</td>
<td>5,2</td>
<td>4,42</td>
<td>3,98</td>
<td>350</td>
<td>510</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>17,54</td>
<td>7,5</td>
<td>6,98</td>
<td>6,28</td>
<td>47,5</td>
<td>277,5</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>15,76</td>
<td>4,6</td>
<td>3,54</td>
<td>2,68</td>
<td>111</td>
<td>300</td>
<td>191</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>14,3</td>
<td>6,62</td>
<td>5,96</td>
<td>4,42</td>
<td>2,5</td>
<td>77,5</td>
<td>47,5</td>
</tr>
<tr>
<td>5</td>
<td>29,5</td>
<td>11,73</td>
<td>3,17</td>
<td>3,12</td>
<td>1,36</td>
<td>0</td>
<td>10</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 1a. Yarn taper board generated by Uster Tester apparatus - example, 100% CO yarn - fineness 30 tex - real size 1741 x 1048 pxl, resolution 300 dpi.

Figure 1b. Magnified yarn board generated by Uster Tester apparatus - example - 100% CO yarn - fineness 30 tex, real size 1763 x 1049 pxl, resolution 300 dpi.

Figure 2a. Standard yarn board (CSN) – grade A, 100% CO yarn - fineness 30 tex; original size 1547 x 2677 pxl, resolution 300 dpi.

Figure 2b. Standard yarn board (CSN) – grade F, 100% CO yarn - fineness 30 tex; original size 1547 x 2677 pxl, resolution 300 dpi.
Table 2. Spectrograms and generated yarn boards of yarn used for experiment.

<table>
<thead>
<tr>
<th>Yarn No.</th>
<th>Spectrogram</th>
<th>Yarn board and its subjective evaluation</th>
<th>Magnified yarn boards</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="https://example.com/spectrogram1.png" alt="Spectrogram" /></td>
<td>CV_{m} = 18.29 % Combination of cumulous spectrum and characteristics spectrum (a chimney) on short wavelength</td>
<td>Moiré effect and short-term stripiness</td>
</tr>
<tr>
<td>2</td>
<td><img src="https://example.com/spectrogram2.png" alt="Spectrogram" /></td>
<td>CV_{m} = 17.54 % Typical cumulous spectrum on short wavelengths</td>
<td>Short-term stripiness</td>
</tr>
<tr>
<td>3</td>
<td><img src="https://example.com/spectrogram3.png" alt="Spectrogram" /></td>
<td>CV_{m} = 15.76 % Characteristic spectrum on short wavelength</td>
<td>Clear moiré effect</td>
</tr>
<tr>
<td>4</td>
<td><img src="https://example.com/spectrogram4.png" alt="Spectrogram" /></td>
<td>CV_{m} = 14.3 % Cumulous spectrum on long wavelengths</td>
<td>Stripiness</td>
</tr>
<tr>
<td>5</td>
<td><img src="https://example.com/spectrogram5.png" alt="Spectrogram" /></td>
<td>CV_{m} = 11.73 % Spectrum without fault</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3a.** Real yarn board – yarn without fault, 100% CO yarn – fineness 30 tex; original size 3381 x 2536 pxl, resolution 300 dpi.

**Figure 3b.** Real yarn board - yarn with moiré effect, 100% CO yarn – fineness 30 tex; original size 3381 x 2536 pxl, resolution 300 dpi.
of the program. The area variation curve is constructed from external variation coefficients of grayness in dependence on observed square areas according to formula (1). All presented yarn boards are used. The image is divided into squared fields with the consequently growing area. Minimum number of observed square fields into sample was 100; maximum square field area was 2.19 cm². In the case of semivariograms, applied to yarn board generated from Uster Tester here, the image is divided into square fields of selected size step x step pixels. The average grayness degree \( \langle z(x) \rangle \) is calculated in each field. From the obtained values, the centered semivariogram in the given direction is calculated according to formula (2). We used the step 3 pxl and step 30 pxl. We selected the step 3 pxl because it corresponds to the yarn width in the image, and step 30 because it corresponds to 0.25 cm in the image; in our opinion it is the smallest possible area which a human eye can see and evaluate.

**Results and its discussion**

**Yarn taper boards and magnified yarn boards generated by Uster Tester**

The area variation curves of grayness degrees constructed from the yarn taper boards and the magnified yarn boards are mentioned in Figures 4a and 4b.

The courses of area variation curves of grayness degree constructed from the yarn taper board generated by the Uster Tester IV-SX are very similar (see Figure 4a). It is obvious, from this figure, that the curve for faultless yarn (No. 5) lies lower than others. In the case of regular yarn, the yarn taper board has the best appearance; grayness degrees fluctuate less compared to the yarn board with irregular yarn. Thus, the area variation curve for this yarn taper board lies lowermost. The curves for faulty yarns (faulty yarn taper boards) overlap and there is not much difference between them. It means the area variation curve is not a suitable tool for recording these faults in the yarn board generated by Uster Tester IV-SX.

The area variation curves of grayness degrees constructed from the magnified yarn boards fluctuates periodically. The reason is that the magnified yarn board is an enlarged part of the yarn taper board and thus has more visible yarn winding on the board compared to the non-magnified one. Therefore, we can say the curve records the yarn winding on the board. There is no difference among curves in terms of yarn irregularity. In neither of these cases is the area variation curve a suitable tool for the evaluation of yarn taper board generated by the Uster Tester IV-SX.

Directional semivariograms of grayness degrees constructed from yarn taper boards and magnified yarn boards are mentioned in Figures 5a, 5b, 6a and 6b. From each image, the area of size 650 x 650 pixels was evaluated in the case of the yarn taper board, and the area 1000 x 1000 pixels in the case of the magnified yarn board. The observed area was in the center of the image.

The courses of semivariograms of grayness degrees constructed from the yarn taper boards with step 3 pxl are also similar (see Figure 5a). In works [28] and [1], it was found out that increasing the linear character of the course of semivariogram curve in the direction of the columns in combination with periodic course of semivariogram in the direction of row records longitudinal stripes in the image of textiles. In this case, semivariograms with step 3 pxl has a similar character (see Figure 5a). It can be said, stripes in the yarn boards generated by Uster Tester were also recorded. Stripes express winding of the yarn on the board, but the yarn irregularity was not probably recorded. This holds also in the case of semivariograms constructed from magnified yarn boards (see Figure 6a).

Curves of semivariograms with step 30 pxl have a little different behavior compared to semivariograms with step 3 pxl; they also differ in their location in the graphs. In this case, the position of the courses of semivariograms of grayness degrees from yarn taper boards (see Figure 5b) corresponds to the quality of yarn on the board. The curve of yarn without faults lies lowest in the case of all types of semivariograms, whereas the curve of yarn containing cumulous spectrum and short stripiness has the highest values. As already mentioned, the irregularity of yarn on the board is converted to the grayscale. In the case of irregular yarn, the color image of yarn board is unbalanced. It contains large number of areas with white color representing
the yarn and its irregularity. The fluctuation of average grayness degrees in observed squared fields is higher compared to yarn without faults. Therefore, the curves of semivariograms lie higher in the graph. This fact is most visible on semivariogram in the direction of rows, columns and omni-semivariogram.

In the case of semivariograms with step 30 pxl constructed from the magnified yarn boards (see Figure 6b), the curves of semivariograms in direction of columns have a growing character, their course diverges from the linear one with increasing irregularity of yarn. Therefore, curves of
the magnified yarn boards with higher yarn unevenness exhibit more unsettled appearance in comparison with the yarn taper board. Due to higher irregularity of yarn displayed on the board, the variation of grayness degrees in individual square fields in direction of columns is higher in comparison to the magnified yarn board with lower yarn irregularity.

Figure 6a. Semivariograms – magnified yarn board generated by Uster Tester IV-SX – step 3 pxl.

Figure 6b. Semivariograms – magnified yarn board generated by Uster Tester IV-SX – step 30 pxl.
The curves from etalons (grades A to F, see Figure 7a) are similar. The positions of the curves are nearly identical, with the exception of etalon F (the worst appearance), where the curve has the highest values. Comparing curves from etalons (grade A, Figure 7b), we can see that the behavior of the curves is dependent on yarn fineness on the etalon as well as yarn winding.

The results showed that the area variation curve is not a suitable tool for objective evaluation of the appearance of the yarn wound on the board even in this case. The curves from etalons (grades A to F, see Figure 7) are similar. The positions of the curves are nearly identical, with the exception of etalon F (the worst appearance), where the curve has the highest values.

**Real yarn boards**

The area variation curve of grayness degree constructed from the real yarn board image is mentioned in Figure 8 (red and blue curves).

The area variation curve from the real yarn board with the yarn without fault has lower values and shows regular fluctuation compared with the curve from the real yarn board with moiré effect (see Figure 8). The regular fluctuation of the curve is caused by individual winds of regular yarn (winding), which the curve records. In the case of irregular yarn (moiré effect), this fluctuation is subdued due to irregularity of yarn. Thanks to the moiré effect, the appearance of yarn on the board is unbalanced—contains a lot of periodically repetitive thick and thin places. Therefore, average grayness degrees vary more between the observed square fields, and due to this the area variation curve has higher values compared to the curve from the yarn without fault. But, we must say that the difference between the positions of both area variation curves is not too significant.

We can compare the behavior of the area variation curve with curve of ideal yarn board. For this reason, the simulated ideal yarn board was constructed (see Figure 9a). The white stripes in the image represent a yarn. It is considered the absolute ideal state; it means neither irregularity nor hairiness of the yarn is taken into account. The stripe width corresponds to the

**Real standard yarn boards (etalons)**

Area variation curves of grayness degrees constructed from real standard yarn boards (etalons) from CSN 80 07 04 (yarn fineness 30 tex) grade A to grade F are shown in Figure 7a. The curve from etalons (grade A) of all fineness is shown in Figure 7b.

![Figure 7a. Area variation curves – etalons (A-F) - yarn fineness 30 tex.](image)

![Figure 7b. Area variation curves – etalons (grade A).](image)

![Figure 8. Area variation curves – real yarn boards – yarn fineness 30 tex.](image)
square fields of the pre-set size. Even though in some cases the area variation curve can be used for evaluation of surface unevenness of woven fabric [20], based on these results we can say that the area variation curve is not a suitable tool for the evaluation of yarn board appearance. The difference between curves constructed from the boards of deteriorating quality is not much significant. Semivariograms seem to be a more suitable tool for the evaluation. The position and behavior of the curve of semivariogram corresponds to quality of yarn on the board, but the type of irregularity is not possible to be identified. Also the piece of knowledge about behavior of semivariograms presented in work [1] was confirmed here.

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References


yarn width on the real yarn board – i.e. 5 pxl. The width of black stripes corresponds to the distance between winds of yarns; it is 7 pxl. The colors were gained from the image of the real yarn board.

The area variation curve of grayness degrees constructed from a simulated ideal yarn board is mentioned in Figure 9 (black dot curve). The periodical course of the curve records individual winds of yarn on the board. The period nearly corresponds to the period of area variation curves of grayness degrees constructed from the real yarn board with the faulty yarn and yarn without fault.

The courses of directional semivariograms of grayness degrees for these real yarn boards together with semivariograms of real standard yarn boards were presented and discussed in work [1]. The behavior of these curves constructed from the simulated ideal yarn boards was also analyzed. The course of semivariogram was influenced by yarn fineness and winding density in combination with the parameter step. It was found out that a small size of the parameter step is less suitable for evaluation of the yarn appearance on used yarn board. The course of semivariogram recorded more the structure of yarn winding on the board – regularity of winding. With deteriorating grade of yarn appearance, the curves of semivariograms with used step 15 pxl showed higher values and fluctuating course.

Conclusion

A study of using the area variation curve for the evaluation of the appearance of yarn wound on the board was presented with the aim to extend the obtained piece of knowledge. For this reason, we used the same etalons of yarns from ČSN 80 0704, the same real yarn boards with yarn of various quality as in work [1] for which this article follows. To enlarge and confirm the results, we also used images of the yarn taper board in addition to the magnified yarn taper board appearance generated by the Uster Tester IV-SX instrument based on measurement of yarn with various irregularities. These generated boards were also evaluated by means of directional semivariogram from the point of view of yarn irregularity. All yarn boards were scanned and then, using the script in Matlab, the area variation curves and directional semivariograms (only in the case of generated yarn board) were constructed. These functions express fluctuation of grayness degrees of image in dependence on the size of evaluated square fields or on various distances between


Introduction

Computer-aided design (CAD) is the use of computer technology for the process of design and design documentation. CAD software, or environments, provides the user with input-tools for the purpose of streamlining design processes, i.e. drafting, documentation, and manufacturing processes. CAD output is often in the form of electronic files for print or manufacturing.

CAD environments often involve more than just shapes. As in the manual drafting of technical and engineering drawings, the output of CAD must convey information, such as materials, processes, dimensions, and tolerances, according to application-specific conventions. CAD is an important industrial art extensively used in many applications, including automotive, shipbuilding, and aerospace industries, industrial, textile and architectural design, prosthetics, and much more. CAD is also widely used to produce computer animation for special effects in movies, advertising, and technical manuals [1]. All professional CAD packages for woven textiles will be able to achieve basic fabric simulation and production output. A good CAD system should enable you to create design (dobby and jacquard woven fabric) ideas quickly and easily to enhance the way you work. The differences among competing systems fall mainly into the following categories: ease of use; speed of operation; flexibility of operation; advanced features; technical support; and ongoing software development.

Computer simulation or prediction is oriented on standard woven fabrics, technical textiles, and composites. This article focuses on the presentation of software ProTkaTex and its use in the prediction of woven fabric properties. The software implements a generalized description of the internal structure of woven fabric on the unit cell level, integrated with mathematical models of the fabric relaxed state. User can calculate selected mechanical and end-use properties of doby and jacquard woven fabric as well as can evaluate fabric behavior before real weaving. The major challenge is to develop software that industry will use in design centers for creation and development of new fabric structures for technical as well as clothing application.

Abstract:

Fabric properties and fabric structure prediction are important in each industry domain. Generally all professional CAD packages for woven textiles system will be able to achieve basic fabric simulation and production output. A good CAD system should enable you to create design (dobby and jacquard woven fabric) ideas quickly and easily to enhance the way you work. The differences among competing systems fall mainly into the following categories: ease of use; speed of operation; flexibility of operation; advanced features; technical support; and ongoing software development. Computer simulation or prediction is oriented on standard woven fabrics, technical textiles, and composites. This article focuses on the presentation of software ProTkaTex and its use in the prediction of woven fabric properties. The software implements a generalized description of the internal structure of woven fabric on the unit cell level, integrated with mathematical models of the fabric relaxed state. User can calculate selected mechanical and end-use properties of doby and jacquard woven fabric as well as can evaluate fabric behavior before real weaving. The major challenge is to develop software that industry will use in design centers for creation and development of new fabric structures for technical as well as clothing application.

Keywords:

Fabric geometry, weave, warp, weft, property, simulation, prediction

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the relaxed and deformed state of 2D- and 3D-woven (see Figure 1), two- and three-axial braided, weft-knitted and non-crimp warp-knit stitched fabrics [16,18,38]. Realistic models have application in the design and manufacture of textile composites. A composite material is one that is made by combining two existing materials: in a fiber-reinforced composite, stiff, strong fibers form one part of the composite, reinforcing the other. In manufacturing, it is common for this reinforcing material to be supplied in textile form, woven from ‘yarns’ made from the fibers [22,23].

Some modules of CAD system are focused on simulation of 3D-woven fabrics with consideration of weaving technological boundary conditions: quick check up of the feasibility of geometry from 3D-woven fabrics; prediction of woven 3D structure and quality for each position of geometry; optimization of parameters of the 3D-woven fabric (thread sizes, weave, and thread distances) by simulation [19]. The packages are dedicated for the design and manufacture (CAD/CAM) of advanced textile structures based on the use of conventional weaving technology. It has been used for the design and manufacture of 3D textile structures, with both solid and hollow architectures, and non-crimp composite reinforcement [22,23]. Software packages can be used for the prediction of standard gray fabric properties for technical and clothing applications. In this case, the software can predict selected properties and fiber parameters in module fiber, selected yarn properties and parameters in module yarn, selected fabric properties and parameters in fabric module. The system contains databases of fiber properties and fabric weaves, and the prediction is based on the complex of theoretical and regression models. The material and technological parameters for different materials, yarns and fabrics are included. The system is mainly used for the optimization of fabric design based on virtually created fabric [20].

**Prediction of woven fabric properties: software ProTkaTex**

ProTkaTex software can be applied for the prediction of selected mechanical and end-use woven jacquard fabric properties with knowledge of the yarns’ properties and fabric interlacing. ProTkaTex was developed at the Faculty of Textile Engineering, Technical University of Liberec. The software is compatible with common CAD jacquard and dobby weaving design systems. ProTkaTex enables 3D visualization of fabrics based on the input yarn parameters. It is used for properties, prediction on the basis of combination of mathematical modeling and experimental research [2,4,31]. The major challenge is to develop a software package that industry will use in design centers for the creation and development of new fabric structures for technical as well as clothing application.

In comparison with the above-mentioned software packages, this software is focused on the determination of standard dobby fabrics as well as jacquard fabrics, and is not focused on the description of textile composite. At this stage, the weave (small and big patterns) covers the structure of single-layer woven fabrics. It is able to evaluate the jacquard pattern with unlimited number of warp and weft threads. On the basis of definition and evaluation of individual interlacing pores in repeat defines the fabric structure and distribution of interlacing points, which influence mechanical and end-use properties. The software consists of three modules: yarn definition, fabric properties, and weaves (design). For the prediction of selected woven fabric properties, it is necessary to know basic input yarn properties. Warp and weft threads are defined on the basis of: type of yarn, fiber packing density $\mu$ [\text{f}}, yarn count $T$ [tex], specific density $r$ [kg/m$^3$], yarn strength $F_{pr}$ [N or N/tex], yarn elongation $E_{pr}$ [%], and yarn irregularity $CV$ [%]. Definition of fiber packing density: inside of the textile fibrous assembly or inside of some spatial part of them, there lies fiber volume $V$. Total volume of this body is called $V_c$. The compactness of this body is characterized by the ratio between these two volumes and is known as fiber packing density. (Note: alternatively, this value is called the packing ratio or volume fraction.) Evidently, the fiber packing density value must lie in the interval from 0 to 1 [4]. Type of yarn is evaluated by technology as well as yarn structure (staple yarn, multifilament yarn, etc.). Software ProTkaTex distinguishes the technologies: combed, carded, and open-end. Based on experimental and theoretical research work [4,32,35], different types of yarn were analyzed (on the basis of threads cross-section evaluation, see Figures 2 and 3) and their construction parameters, and mathematical equations were prepared for yarn parameters prediction. Theoretical expressions of individual parameters of yarn (fiber packing densities, compression of yarn in relaxing state before weaving as well as in fabric, diameter of threads) were compared with experimental parameters that followed from real cross-section of yarn and woven fabric [5-7].
**Weave definition and prediction of woven fabric properties**

Woven fabric weave determines the manner of the thread’s interlacing in the fabric [2]. Definition of individual pores in weave – expression of pores frequency in weave (in rows and in columns) – is used for description of threads interlacing by mathematical equation in this software. In the woven fabric weave, exists only four structural models of interlacing [33], see Figure 4. Dobby as well as jacquard pattern is possible to create by various combinations of these structural pores in repeat. Jacquard design is not possible to create in ProTkaTex. The software is compatible with CAD jacquard design systems (EAT, NedGraphics, Arachne, ScotWeave, etc.), where pattern has to be saved in one of the following formats: TIFF, BMP, JPEG (see Figure 5).

Jacquard weave in the above-mentioned format (see Figure 6) can be opened in module “weave” and then converted into a format required for fabric properties prediction in ProTkaTex. This software uses its own format, VZB.

Description of woven fabric properties and parameters is based on the complex of theoretical and regression models. Prediction is based on the knowledge of yarn parameters and interlacing of individual threads in dobby and jacquard pattern. Calculation of individual fabric properties and mathematical formulations were created on the basis of analysis of areal and spatial fabric geometry. As mentioned above, the software calculates selected properties for dobby as well as jacquard woven fabric. It is possible to predict the following properties of fabrics: relative wave height [\(\text{cm}\)] (separately for warp and weft system), warp and weft density [treads/100mm], weight of fabric [g.m\(^{-2}\)], cover of fabric [%] (separately for warp and weft system too), crimp of threads in fabric [%] (warp and weft), fabric thickness [mm], fabric roughness [\(\mu\text{m}\)], fabric strength [N/5cm] (for warp and weft direction), and fabric elongation [%] (for warp and weft direction). For presentation of individual results of prediction, the above-mentioned properties were selected. In the above-mentioned graphs we can see fabric properties behavior and comparison of theoretical values with experimental values. Parameters of fabric samples: All fabrics are in plain weave. Material composition: 100%PP yarn and 100%CO yarn in three counts 20tex, 29,5tex and 45tex in both directions.

**Weight of fabric**

Calculation of weight of fabric in this software is based on the warp and weft sett and on the yarn count as well as yarn crimp [31]. The software distinguishes two kinds of fabric weight: weight of linear meter of fabric [g.bm\(^{-1}\)] and weight of square meter of fabric [g.m\(^{-2}\)].

**Fabric thickness**

Fabric thickness is defined as perpendicular distance to the fabric, which determines the dimension between the upper and lower side of the fabric. Prediction of fabric thickness depends on fabric geometry description. Mathematical description is based on definition of binding wave in repeat and threads’ waviness in interlacing [37]. Threads’ deformation in interlacing

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**Figure 4.** Principle of X-Ray Tomography.

**Figure 5.** Principle of X-Ray Tomography.

**Figure 6.** Principle of X-Ray Tomography.

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is dependent on the yarn structure and fabric input parameters (weave, warp and weft waviness, warp and weft sett) [4,33]. In the following model (1), the main influence is from yarn diameter and weft and warp waviness.

\[
\text{thickness} = \left[ \frac{d_o + d_u}{2} - \frac{c_1}{2} \right] \left[ \frac{d_o + d_u}{2} - (1 - c_1) \right] f_m = \beta
\]

where \(d_o\) – warp diameter, \(d_u\) – weft diameter, \(e1\) – warp waviness, \(f_m\) - interlacing coefficient, \(\beta\) – yarn compression in fabric (the yarn deformation in interlacing).

**Fabric elongation**

Prediction of fabric elongation in the warp and weft direction is defined as a fabric extension for maximum strength (the breakage) to the original length of fabric. Fabric elongation in warp and weft direction depends on yarn elongation and yarn interlacing in fabrics. Calculation of fabric elongation is based on definition of threads’ crimp and level of threads’ interlacing (which is necessary to evaluate the number of interlacing parts as well as float part in repeat [31]).

**Fabric strength**

Prediction of fabric strength in warp or weft direction depends on warp (weft) yarns and warp (weft) sett. The influence of second system on fabric strength value is neglected. Woven fabric strength does not correspond to the sum of yarn’s strength per fabric width unit in straining direction only. Relation between fabric and yarn strength is corrected by coefficient of utilization of yarn in fabric in warp (weft) direction. It is assumed that coefficient includes influence of material and fabric weave.

**Fabric roughness**

Roughness is a surface micro-geometry and is defined as the sum of unevenness (geometric deviations) of the surface with relatively small distances. It is an important parameter influencing subjective hand feeling and is connected with behavior of textiles’ layers in mutual contact. Calculation of roughness is based on the definition of structural pores in repeat, fabric geometry description, threads’ interlacing as well as yarn irregularity [37].

![Figure 7. Principle of X-Ray Tomography.](http://www.autexj.com)

![Figure 8. Principle of X-Ray Tomography.](http://www.autexj.com)

![Figure 9. Principle of X-Ray Tomography.](http://www.autexj.com)

![Figure 10. Principle of X-Ray Tomography.](http://www.autexj.com)
\[
\text{Fabric Roughness}[\mu m] = \left( \frac{\sum p_i \times \text{Roughness } p_i + \sum n_{i,a} \times \text{Roughness } n_{i,a} + \sum (p_{i,a} + p_{i,a}) \times \text{Roughness } p_{i,a} + \sum n_{i,a} \times \text{Roughness } n_{i,a}}{100 + 100 - CV \times 10^2} \right)
\]

where \(D_{u.o}\) [threads / 100mm] – weft, warp density, \(p_{i,a}\) – pores in weave (definition of interlacing cell in repeat), CV [%] – yarn irregularity.

\section*{Conclusion}

The ProTkaTex software provides an integrated description of the internal geometry of dobby and jacquard fabric and their properties. It is one of the few software packages that are able to characterize and determine the behavior of complicated jacquard patterns in selected properties. The major challenge is to develop a software product that industry will use in design centers for the creation and development of new fabric structures for technical as well as clothing application.

At present are elaborated additional properties and their mathematical formulation that will be implemented in software and extend the existing possibilities of prediction. Software is open to be used in further developments of creation and prediction of new fabric structures and their properties.

\section*{Acknowledgment}

This work was supported by the project Textile Research Centre 1M0553 and by the project GACR 106/09/1196.

\section*{References}


\section*{Figure 11. Principle of X-Ray Tomography.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig11.png}
\caption{Comparison of experimental and predicted fabric roughness}
\end{figure}
Abstract:

The article focuses on a new approach for characterization and evaluation of lateral yarn deformation. A small review about theoretical description and measurement possibilities will be introduced. The evaluation of yarn compression will be done by three innovative methods (lateral deformation of yarn between two parallel plates, simulation of binding point of fabric, cross-sectional analysis of real fabric). The analysis of yarn deformation will be carried out for a set of samples in combination of fiber material, yarn count and given fabric structure.

Keywords:
Yarn diameter, lateral deformation of yarn, innovative measurement principals.

1. Introduction to fabric structure

The woven fabrics structure is complicated due to its complex hierarchy. There are no models, which are able to describe the structure from the fibers through the yarns, and to the fabric. Usually the yarn is used as an elementary building unit of the structural model of the fabric. The fineness \( T \), twist \( Z \) and diameter \( d \) are the basic geometrical characteristics describing a yarn. The diameter is considered only as a theoretical idea. For evaluation of the yarn diameter, it is necessary to know the packing density \( \mu \) [1,9].

The simplified assumption, that the yarn is compact, solid and circular cross-section, is implemented for a description of binding point geometry. The troubles with establishing the yarn diameter originate in the incompactness of yarn structure. Some air gaps are found between the fibers; the yarn cross-section (especially in binding point) also is not a circle. In the binding points, the deformation of the cross-section and the compression of fibers are considered.

In the stretched state of fabrics, yarns compress each other at their cross-over points. The lateral compression force at the cross-over points is generated by the yarn tension. Internal tension in fabric structure is given by the balance of forces, which depends on different types and levels of deformation during fabric production stages and its use. The typical deformation of the yarn cross-section is generally caused by the combined effect of compression, extension, bending and torsion.

Main aim of this work is to report about possibilities, which can be used for measuring the lateral deformation of yarn. The evaluation of yarn compression will be done by three innovative methods (lateral deformation of yarn between two parallel plates, simulation of binding point of fabric, cross-sectional analysis of real fabric). The experimental results for the selected material, yarn count and fabric structure will be presented.

2. Yarn cross-section deformation

The nearly circular yarn cross-section is due to change of compression to a more flat profile. A lot of geometrical models do not include this phenomenon and the so-called free yarn geometry is assumed. Yarn flattening is important from the point of view of selected fabric parameters evaluation, modeling and design. It is, for example, fabric porosity, air permeability and mechanical characteristics in terms of ultimate and user range loading.

2.1 Models

The width \( a \) and height \( b \) are defined for the description of yarn cross-section deformation. The circular cross-section of the “free” yarn (Figure 1a) is changed into a shape, which can be substituted by Kemp’s cross-section (oval of two half-circles with semi-diameter \( b \) and two abscissas of length \( a-b \), Figure 1b), elliptical or lens shape (Figure 1c, d) [1].

It is possible to define relative enlargement and relative compression:

\[
\varepsilon_1 = \frac{(b-d)}{d} \quad (1)
\]

\[
\varepsilon_2 = \frac{(a-d)}{d} \quad (2)
\]

The area \( S \) and the perimeter \( L \) of these shapes can be easily calculated.
2.2 Geometrical hypothesis

For the relationship between the shapes, two alternative hypotheses about constant area and constant perimeter are proposed. This hypothesis can be described as a function of relative enlargement $e_1$ and relative compression $e_2$.

Constant area (cross-sections before and after deformation have the same area) subsequently holds:

$$S = \frac{\pi d}{4} = S_{\text{deformed yarn}} \quad (3)$$

The relation between relative enlargement and relative compression is derived:

- **Kemp**
  $$e_2 = \frac{e_1^2}{(1 - \pi/4)} + e_1(1 - \pi/2)/(e_1 + 1), \quad (4a)$$

- **ellipse**
  $$e_2 = -e_1/(e_1 + 1). \quad (4b)$$

It is impossible to express the relative enlargement explicitly for a lens; therefore, the equation was solved numerically:

$$e_2 = 1.11/(e_1 + 1)^{1/4} - 1. \quad (4c)$$

Constant perimeter (cross-sections before and after deformation have the same perimeter) subsequently holds:

$$L = \pi d = L_{\text{deformed yarn}} \quad (5)$$

The relation between relative enlargement and relative compression is derived:

- **Kemp**
  $$e_2 = \frac{e_1(1 - \pi/2)}{1}, \quad (6a)$$

- **ellipse**
  $$e_2 = \sqrt{2 - (e_1 + 1)^2 - 1}. \quad (6b)$$

- **lens**
  $$e_2 = \sqrt{(\pi/2)^2 - 4/3 \ (e_1 + 1)^2 - 1}. \quad (6c)$$

Lomov [7] proposes the relation between relative enlargement and relative compression empirically:

$$e_2 = 1/(e_1 + 1)^n - 1 \quad \text{for } n=1, 2... \quad (7)$$

The estimation of these hypotheses is based on the assumption of circular cross-section of “free” yarn. The circle has minimal perimeter for the same area and maximal area for the same perimeter, compared to other plane figures. The cross-section changes are caused not only by changes in shape but also due to relaxation of radial forces. These forces originate from the helix structure of the fibers in the yarn.

From the first hypothesis of “constant area”, we conclude that the perimeter of the deformed cross-section must be increasing; the volume of inter-fibers pores does not change, it means that the packing density decreases. It would be a particular effect, which eliminates the action of radial forces relaxation.

From the second hypothesis of “constant” perimeter, the area of the deformed cross-section must be decreasing; the packing density increases, because the number of inter-fiber pores decreases and the contacts of fibers increase. It means the destruction of the original (primary) yarn structure turn up.

3. Experimental methods

There exist various methodologies for evaluation changes in yarn cross-sections. A change of yarn diameter under tension in the yarn-axis direction was studied in many pieces of research. They are mostly based on optical system or mechanical detection. Only few of them are described and their results are shown in this article.

There is a group of methodologies, which is based on fabric analysis. One of them is the judgment of fabric thickness before and after biaxial tension, which is described in [4]. The cross-sectional analysis of fabric in freeze state is another approach to gain information about yarn’s deformation. Fabric can be fixed by soft or hard methods. The experiment is based on the analysis of frozen fabric structure in terms of cross-sectional analysis or surface analysis in the third main fabric direction [5]. The improved possibility of novel stress-freezing technique for studying the compression behavior of fabrics is described in [10]. The biggest advantage of this modified method is the possibility of deformed fabric fixing.

Fixing of fabric in stressed state is limited and therefore the simplified approaches were found to see the influence of selected factors and forces. Methodologies, which take not only compression but also bending into consideration, are wire method, V wire method, three-rod unit and simulation of binding point in hollow block [2] and [4].

The deformation of yarn between two parallel plates is the highest simplification of a real state in balance of forces at a cross-over point. In this case, only complexional forces cause the deformation of yarn. There are several methods by which the thickness of yarn can be measured. Using of a rotation drum and feeler, in which the yarn thickness is measured by passing the yarn around the drum’s circumference with the feeler pressed very gently against the yarn, has been mentioned in [8]. The KES F3 system allows the measurement of yarn compression in terms of yarn thickness as a function of compression load [3,4]. In case, the information about yarn thickness (minor yarn diameter $b$) is not enough and the knowledge of yarn widening (major yarn diameter $a$) is demanded then it is possible to use special equipments, which offer measuring the change in yarn diameter in both main directions under higher pressure [2].

3.1 Analysis of weave cross-sections

The method used for the detection of the internal weave structure is based on the analysis of the weave cross-sections [4,5,7]. The measuring parameters are shown in Figure 2. The fabric cross-sections were prepared by the method of “soft” cross-sections, where the blend of bee wax and paraffin, as fixing medium, was used [1,9]. These cross-sections usually have a thickness of 30 mm.

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3.2 Assessment of yarn flattening caused by compression and bending

The wire and V wire method is the simplification of real state in fabric binding point. One of the cross-over yarns is substituted by absolute stiff wire because of the factors influencing elimination. A steal wire is usually fixed on a horizontal base and yarn is hanged on the wire with tension. The angle between the yarn and the horizontal level is 30°, which is approximately equal to the averaged yarn-intersecting angle in various weaves. A V-shaped groove at the cross-over area is more close to the real intersecting state of the yarn in fabric binding point. The yarn thickness is measured by a needle sensor contacting at the top of the yarn surface with a small compression force [4,9].

The alternative possibility based on the V wire method is using the three-rod unit mounted, for example, on the Instron Tensile Tester. The three-rod unit consists of a rod fixed to a horizontal base and two rods of the same diameter placed parallel to the bottom one. It is spaced at the center of the three rods that form an equilateral triangle. The unit enables the measurement to be made of the changes in both minor and major diameters of a yarn bent over the three-rod unit subjected to increasing extension [4].

Simulation methodology of real fabric binding points goes out from idea that the yarns are crossed in a hollow block and various forces realize their deformation. Arrangement of experiment is shown in Figure 3. The hollow block is placed under a macroscope and the measurement of change in yarn's diameters is realized in the system of image analysis [2]. Yarn is guided in between two opposite corners that are placed in position of block diagonals. One end of the yarn is fixed by clumps and the other is guided over a small ideal pulley with a small pretension. The simulated binding point is placed in the hollow block center. The loading of the yarn sample is realized by various weights.

3.3 Yarn compression between two parallel plates

The other method for the simulation of stress in the binding point is based on the yarn compression between two parallel plates [5,6]. The first prototype is shown in Figure 4. This device is placed under a macroscope holder. The yarn is guided though the measuring zone between two glass parallel plates and is pretended proportionally to the yarn count. The deformation of yarn is the result of loading realized by an upper frame. The upper frame can be connected with various pieces of defined weight and a seven level of loading is available. Sequence of yarn longitudinal views before and after deformation at same place is scanned and the absolute values on scales of two contact thickness meters are read. Sequences of yarn macro-images before and after deformation in terms of yarn diameter d and yarn characteristic proportion a are evaluated. Characteristic proportion b, in other words yarn thickness, after deformation is equal to the value, which describes the difference between the absolute value on the scale of thickness meter without and with deformed yarn between parallel plates under pressure.
4. Experimental material and results

The main idea of this experiment was to use the selected methodologies used for the evaluation of yarn deformation and apply them to a set of fabrics and yarns, which were used for fabric weaving. The results should be discussed and compared with expectations and the influencing factors should be identified.

A set of experimental gray relaxed fabric in plain weave was used for the experiment. Fabrics were produced from 100% CO, 100% PP and 50CO/50 PP 29,5tex staple single ring yarns with a given set of warp (25 thread cm⁻¹) and three level of set of weft (8,8 thread cm⁻¹, optimum 13 thread cm⁻¹ and 17 thread cm⁻¹). One gray relaxed fabric produced with comparable geometrical structure in plain weave from 100%PET 16,5tex staple single yarn was added for the experiment. Analysis of yarn deformation was realized according to the cross-sectional technique described in section 3.1 for both main directions of the fabric (warp and weft). Experimental results are shown in Figure 5a.

Estimation of the level of yarn deformation based on the evaluation of simulated binding point described in section 3.2 was realized for a set of yarn used for fabric production. Yarns were spun by classical ring spinning technology with 29,5tex yarn count from 100% CO, 100% PP and 50CO/50 PP staple fiber material. Three levels of loading force were applied to simulate yarn deformation (1,8 g – 0,07N, 6,8 g – 0,26N and 11,8 g – 0,44N). The obtained data are presented in Figure 5b.

Yarn deformation was also simulated by deformation between two plates mentioned in section 3.3. Hundred percent CO 29,5tex staple single ring spun yarn, which was used for fabric production, was analyzed and an experimental set of 100% CO single staple yarn was added to the lab measurements. It was a set of typical ring spun yarn that was produced with 16,5tex, 20tex and 38tex yarn count. Seven levels of deformed forces were used for the simulation of yarn deformation (10N, 15N, 20N, 25N, 30N and 40N). Summarization of data is given in Figure 5c.

5. Discussion

Figures 5 a, b, c show relationships between relative enlargement and relative compression. The hypothesis for constant perimeter and constant area are compared with experimental data.

The generally known results could be expected. Experimentally analyzed yarn deformations in a fabric binding point are located in the low levels of relative yarn enlargement and compression. It is not possible to decide, if the deformations follow the hypothesis of constant perimeter or constant area. Calculated curves describe that the limited cases are very close to each other in this range of deformations. Experimental data should be placed in a delimited area of both hypotheses. Most of them are under hypothesis of constant perimeter. It is probably caused by the precision of original yarn diameter estimation.
increases. The behavior of fabric produced from blended yarn is more close to the behavior of 100% PP fabric. Differences among experimental data were very small. The verification of significance power of these factors is limited, because the data are very sensitive to original yarn determination.

Using of hollow block for the analysis of yarn deformation is limited from the point of view of estimation of relative compression only. In other words, it is not possible to measure the second parameter describing the level of relative enlargement. Therefore, the second coordinate of the experimental data is equal to zero in Figure 5b. An increased loading force causes the increase of yarn relative compression in contact point. The statistical significance of the fiber material used for yarn production is very low but for verification repeating of measurements should be realized. The blended yarn behavior is much closer to the behavior of 100%PP yarn. The reason can be what’s hidden in yarn production because of used mass fibers mixing. There is a higher number of polypropylene fibers in yarn volume than cotton fibers. It confirms the outputs from the methodology given in section 3.1. The interesting conclusion arises from the comparison of relative deformation obtained from fabric analysis and this method. It seems that the level of normal force in the gray relaxed fabric is very close to the first level of loading force realized here by the weight 1.8 g.

Simulation of yarn between two parallel plates is the most simplified process of real deformation in real binding point. Based on previous experiments and solving force balance, it can be expected that for the description of deformed yarn the cross-section Kemp model and hypothesis of constant perimeter will be desirable. It means, in other words, that the yarn is due to deformation compressed and the pacing density of yarn increases. It can be also expected, that the deformation will increase with the increase in yarn count or loading force. The obtained experimental results are in a good agreement with our expectations. Differences in experimental data results are higher for the higher applied forces. Moreover, the statistical significance of data differences was not verified.

6. Conclusion

In this investigation, the yarn lateral deformation was studied. The experimental data obtained from three selected methodologies were compared. The influence of selected factors was roughly evaluated. There was for analysis used methodology, fiber material, yarn count, applied level of deformation force and fabric structure in terms of set of warp and weft.

It can be concluded (thanks to the realized experiment) that the methodologies give us comparable results, which can be the background for precise modeling of structure and mechanical parameters of fabric. Yarn flattening is important, for example, for estimation of fabric porosity, air permeability and mechanical characteristics in terms of ultimate and user range loading.

Acknowledgment

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References

1. Introduction

Higher production and higher demands of customers on fabric utility value means higher requirements on yarn production quality. Selected fiber material, chosen spinning technology, and all previous operations are necessary to be applied before weaving, since their correct application influences fabric and end-product quality. Performance of warp yarns on a loom during weaving is affected by a number of factors as it is subjected to complex deformation including abrasion, cyclic bending together with tension and impact loading. Controlling yarn’s structural characteristics and examining of level of mechanical parameters together with evaluation of yarn’s weaving-ability is essential. Abrasion resistance and its measurement for raw and sized yarn can help in the judgment of yarn’s weaving-ability.

2. Yarn abrasion

2.1 Testing possibilities

Methodologies used for yarn abrasion resistance testing can be divided into two groups. First group uses a defined abrasion material. Results from this test are comparable [7]. An example of this instrument is Zweigle G 552 tester [2], Wira tester [5] or CTT yarn abrasion tester [9]. Simulation of mechanical behavior on laboratory loom or on its function parts can give results more close to real weaving. On the other hand simulation is limited too. Loom settings, its speed, all interaction among yarns and guiding places are different for various kinds of looms. Representative instrument is Reutlinger Webtester [1]. Simulation of “yarn on yarn” abrasion can help us in understanding the mechanism of yarn damage during yarn on yarn contact. Staff tester of Zweigle [5] simulates the running characteristics of spun yarns and smooth plied yarns. Special method “yarn on yarn” is used for testing of rope or specific yarns made from special synthetic fibers. Measurement can be realized in normal or wet conditions [8]. Zweigle G 522 method was used during the experiment and therefore few things need to be addressed. Usually up to twenty threads are placed in the abrasion tester; thereafter pre-tension is applied (usually 20g or 30g per thread). Everything proceeds automatically: An abrasion roller covered with emery paper traverses in constant rhythmic motion and constant pressure at right angles to the direction at which the test threads are tensioned. The abrasion roller continuously rotates about its own axis so that an abrasive action is not impaired by abraded yarn residue in the emery paper. The computer controls the test procedure and logs the yarn breaks. Special optical sensors are activated when a weight drops down, and number of strokes for all samples is recorded in a database [2].

2.2 Approaches to yarn abrasion description

Abrasion resistance is usually expressed as a number of strokes to yarn destruction. A criterion based on weight reduction is a bit problematic, because limited yarn length is possible to weight. A weight reduction due to abrasion can be easy described thanks to yarn diameter changes. The diameters of original yarn samples and yarns after extension of 50% of the number of strokes for yarn destruction can be observed according to internal methodology IN 32-102-01/01 [10].

The method is based on scanning and processing images of yarn longitudinal views. Color images are transformed through gray-scale to binary images by using Otsu’s method [4]. Fibers that belong to the hairiness sphere are eliminated by morphological operation (erosion, dilatation, opening, and closing of image). All image rows are processed step by step. Number of pixels belonging to yarn is counted. Their original length is recalculated by used calibration. Evaluation of each image row – potential yarn diameter (original yarn diameter $D$, yarn diameter after abrasion $Da$), outlier values exclusion, statistical yarn diameter finding – follows. Yarn diameter as a mean value itself cannot describe diameter change completely. Minimum $Da_{min}$, maximum $Da_{max}$, and mean value $Da$ of yarn rows’ length can qualify yarn dimensions after abrasion.

Abstract:

There exist a lot of methodologies, which can be used for yarn quality testing. Abrasion resistance and its measurement for raw and sized yarn can help in the judgment of yarn weaving-ability. This article concentrates on the possibility of yarn abrasion expression and testing. Relation among fiber material characteristics, selected yarn structural, and mechanical parameters is discussed and a few experimental results are shown.

Keywords:

Structural and mechanical yarn characteristics, yarn abrasion resistance.
Minimum diameter means the shortest row length of imaginary yarn cross-section. Maximum diameter means diameter of cylinder, which can cover the yarn. In other words, it is a difference between the smallest coordinate and the highest coordinate, where black pixel that belongs to yarn is placed in hole image and not only in actual image row. The percentage change of yarn diameter before and after abrasion can express abrasion resistance.

3.1 Experimental material

The idea of this experiment is to prepare yarns from various fiber materials with similar yarn geometrical parameters under comparable condition. A set of one component and blended single and two-ply ring spun yarns was used for the experiment.

Step 1: One-component single ring spun yarns were spun in five levels of yarn count and three levels of Phrix twist coefficient from 100% PET, PAN, VS fibers. The information about the fiber material is shown in Table 1. One-component single ring spun yarns are described in Table 2.

Step 2: Set of blended single and two ply yarns were produced with typical yarn count level 29,5tex, respectively 2x29,5tex and optimal Phrix twist coefficient in five level of blending portion of polypropylene PP and cotton CO fibers. The information about the fiber material is shown in Table 1. The description of this set of yarns is given in Table 3.

$$R_{ij}^{(2,3,\ldots)} = \frac{\det(R_{ij})}{\sqrt{\det(R)}},$$

$$R_{ij}^{(2,3,\ldots)} = \frac{\det(R_{ij})}{\sqrt{\det(R)}},$$

3. EXPERIMENT

The influence of selected factors on abrasion resistance is investigated. The level of influencing factors is evaluated thanks to correlation and ANOVA analysis. Pair and partial correlation coefficient was used for expression of strength and direction of a linear relationship between two random variables. It was calculated according to eq. (1a,b). Pair correlation measures the strength of the relationship between two random variables. It does not take other influencing factors into consideration. Partial correlation is more sufficient, because it measures the degree of association between two random variables, with the effect of a set of controlling random variables removed. ANOVA analysis enables dividing of variance into different components due to explanatory variables. Two-dimensional ANOVA analysis with fixed-effects model was used for data processing.

Table 1. Selected fiber parameters.

<table>
<thead>
<tr>
<th>material</th>
<th>PET</th>
<th>PAN</th>
<th>VS</th>
<th>CO (Egypt Giza 70)</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t/t_a$</td>
<td>1,3/ 1,4</td>
<td>0,9/ 1,17</td>
<td>1,3/ 1,34</td>
<td>1,65</td>
<td>1,88</td>
</tr>
<tr>
<td></td>
<td>(1,36; 1,45)</td>
<td>(1,13; 1,21)</td>
<td>(1,30; 1,37)</td>
<td>(1,53; 1,77)</td>
<td>(1,80; 1,95)</td>
</tr>
<tr>
<td>$r_v$</td>
<td>1360</td>
<td>1170</td>
<td>1520</td>
<td>1520</td>
<td>910</td>
</tr>
<tr>
<td>$l$</td>
<td>38</td>
<td>38</td>
<td>38</td>
<td>31,13</td>
<td>50</td>
</tr>
<tr>
<td>$RF$</td>
<td>53,32</td>
<td>33,97</td>
<td>17,56</td>
<td>40,5</td>
<td>40,42</td>
</tr>
<tr>
<td>$f_v$</td>
<td>0,3</td>
<td>0,33-0,48</td>
<td>0,19</td>
<td>0,19</td>
<td>0,51</td>
</tr>
<tr>
<td>$e_v$</td>
<td>17,51</td>
<td>31,86</td>
<td>30,05</td>
<td>5,95</td>
<td>63,35</td>
</tr>
<tr>
<td></td>
<td>(16,27; 18,74)</td>
<td>(30,63; 33,08)</td>
<td>(29,11; 30,99)</td>
<td>(5,41; 6,48)</td>
<td>(58,13;68,56)</td>
</tr>
</tbody>
</table>

Table 2. Description of one-component single ring spun yarns.

<table>
<thead>
<tr>
<th>material</th>
<th>PET, PAN, VS</th>
<th>PET, PAN, VS</th>
<th>PET, PAN, VS</th>
<th>PET, PAN, VS</th>
<th>PET, PAN, VS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ [tex]</td>
<td>16,5</td>
<td>20</td>
<td>29,5</td>
<td>35,5</td>
<td>42</td>
</tr>
<tr>
<td>$a$ [ktex²/m⁻¹]</td>
<td>50</td>
<td>56</td>
<td>62</td>
<td>50</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 3. Description of blended single and two-ply yarns.
3.2 Testing conditions

Testing of selected fiber and yarn parameters was realized according to the Czech European International Standard. Conditioning of samples was made in respect to ČSN-EN-ISO-2061. Fiber fineness and mechanical parameters were measured according to ČSN-EN-ISO-1973 by Vibroskop & Vibrodyn instruments (gauche length 10mm, pretension selected according fiber material, 50 measurements). Counting of yarn count and yarn twist was realized in agreement with ČSN-EN-ISO-2060, ČSN-EN-ISO-2061. Yarn mechanical parameters were tested according to ČSN-EN-ISO-2062 on Instron tester (gauche length 50mm, pretension selected according yarn count, time of correct test up to 20s ± 3s, 50 correct measurements). Zweigle G 552 instrument was used for measuring number of stokes to destruction (pretension 20g, emery paper P 800 with abrasive grain alpha Al2O3 and loom reed, 60 measurement). Yarn diameter change due to abrasion was studied only for the set of blended yarns. Diameters of original yarn sample and yarn after extension of 50% of number of strokes to yarn destruction were observed according to internal methodology IN 32-102-01/01 [10] (image resolution 548pxl x 704pxl, calibration 2,23µmpxl⁻¹).

3.3 Discussion of experimental results

The relation among fiber parameters, yarn count, yarn twist, and mechanical parameters is well known. Theoretical presumptions were confirmed by many experiments. It is generally accepted that yarn strength is related with fiber characteristics (mechanical parameters, stiffness, friction, and flexural rigidity), yarn structural characteristic (count, twist coefficient, and packing density), and technology of production. Production technology selection influences the level of fiber arrangement. Higher degree of fiber arrangement in yarn means better yarn mechanical properties. Correct level of yarn count and twist is important from the point of view of yarn packing density. Higher compactness of fiber in yarn causes stronger utilization of fiber strength and inter-fiber slippage. Using of stronger, stiffer fiber material with higher yarn count and higher twist leads to stronger yarn with lower elongation. It can be expected that similar assumptions will be valid for yarn abrasion.

Simulation of yarn abrasion straining on a loom was realized using Zweigle G 552 tester. Yarn structure was opened during yarn abrasion and twists were pushed to the ends of the testing zone. Bundle of fibers and its damaged segments created entanglements on the sample body (see Figure 1). Inter-fiber slippage supported by pretension and structure opening tended to break the sample. Knowledge of dimension and the occurrence of thin and thick places on yarn’s body is important. Thick places create trouble while passing through all the guiding places on a loom. Thin places are a risky part of the chain that increases the warp breakages. It is necessary to mention that the images of yarn are transformed from 3D to 2D and therefore dimension of thin or thick places is not fully described. An example of yarn longitudinal view of 29,5tex yarn before and after abrasion due to emery paper is shown in Figure 2 (Figure 2a shows the original yarn sample, Figure 2b the thin place, and Figure 2c thick place of the sample).

Multivariate data analysis (Correlation and ANOVA analysis) was used for data processing. Question of significance of the power of various factors on yarn abrasion resistance was solved in two steps. A set of single yarn samples allows us to judge the influence of fiber material, and structural and mechanical characteristics on abrasion resistance (step 1).

Figure 1. 100% cotton single yarn 29,5tex after 50% of the number of strokes to yarn destruction (calibration 4,72µmpxl⁻¹, resolution of image 548pxl x 704pxl).

a b c

Figure 2. 100% cotton single yarn 29,5tex before and after 50% of the number of strokes to yarn destruction (calibration 2,23µmpxl⁻¹, resolution of image 548pxl x 704pxl).
The effect of blending portion together with plying technology on abrasion resistance can be studied, thanks to comparison of blended single and two-ply yarn results (step 2).

**Step 1:** Influence of selected fiber (fineness \( t_v \), diameter \( d_v \), mass density \( r_v \), flexural rigidity \( RF \), strength \( f_v \), and elongation \( e_v \)) and yarn characteristics (nominal count \( T_{jm} \), Phrix twist coefficient \( a \), experimental count \( T_{exp} \), twist number \( Z \), and mechanical parameters \( F, e \)) on yarn abrasion resistance was investigated for a set of one component single yarns defined in Table 2. Yarn abrasion resistance was expressed as a number of strokes to yarn destruction \( a_s \). Number of strokes is highly correlated with yarn count. Therefore, the ratio between the number of strokes and yarn count was added to data analysis \( a_s \). Correlation map for paired correlation coefficients is shown in Figure 3a and for partial correlation coefficients in Figure 3b.

Thanks to multivariate data analysis, it was found that fiber strength, yarn count, yarn strength, and elongation are significantly related to abrasion resistance (paired and partial correlation coefficients higher than 0.5). It was verified that number of strokes to yarn destruction \( a_s \) is positively correlated with yarn count (partial correlation coefficient 0.64). Influence of twist level is not as significant as we expected. This approach is limited because of a mutually connected factor (multicolinearity), factor’s limited range, and proper selection of technological yarn creation parameters (interdependence yarn count, yarn twist).

**Step 2:** Set of blended single and two-ply yarns is very interesting, since polypropylene is normally not used for blending with cotton fibers. These two kinds of fibers are dissimilar in many characteristics, but an otherness in mass densities and mechanical parameters give blended yarns attractive parameters. When we use well-known relation among fiber mass density, fibers characteristics (e.g., fineness \( t_v \), strength \( f_v \), elongation \( e_v \)), and yarn’s parameters (e.g. count \( T \), twist \( Z \), tenacity \( F \), and elongation \( e \)), we can find interesting connection. Same fineness of cotton and polypropylene fibers means higher diameter of polypropylene fibers. Polypropylene fibers have higher tenacity and elongation than cotton fibers, because of their chemical nature. Same yarn count and same level of twists means higher number of polypropylene fibers in yarn cross-section. This phenomenon leads to higher diameter and higher tenacity of polypropylene yarn. Dependence of yarn tenacity on blending ratio can be predicted by Hamburger’s theory [10]. Modeling of other mechanical parameters (e.g., elongation, abrasion resistance) is problematic and exists only in regression equation.

Figure 4a, b, c shows relationships between yarn tenacity, yarn elongation, abrasion resistance, and blending portion of cotton fibers for single and two-ply yarns. The obtained results
of mechanical parameters correspond with our expectation. It is evident, that two-ply yarns have higher tenacity, comparable elongation, and higher abrasion resistance than single yarns. Tenacity of yarns decreases in respect to increasing blending portion of stronger component (PP); and that after reaching critical blending portion, point increases. Higher portion of stiffer stronger polypropylene fiber in yarn leads to lower elongation. General conclusion for dependence of abrasion resistance on blending portion was not found. Only semi-linear function can be suitable for trend description. Blending portion 35PP/65CO seems to be optimal from the point of view of abrasion resistance and other mechanical parameters.

Analysis of yarn diameters before and after abrasion shows interesting results. Percentage of yarn diameter change describes yarn's abrasion resistance in terms of weight loss. Diameter comparisons \((D-Da)/D \times 10^2\), \((D-Da_{min})/D \times 10^2\), and \((D-Da_{max})/D \times 10^2\) show, that the change due to abrasion is more significant in case of single yarn. Typical trend of yarn diameter change in terms of blending portion can be found only for comparison of mean diameters \(D\) and \(Da\). Diameter \(D\) decreases if blending portion of PP fibers decreases. Diameter change increases if blending portion of PP fibers decreases. Diameter reduction due to abrasion is more obvious in case of single 100%CO yarn and is about 20% (for 100% PP only 10%). Two-ply yarns show lower reduction of yarn diameter and is in a range from 1% to 3%. Evaluation of diameter \(D\) and \(Da_{min}\) indicates that 40% reduction of diameter in case of single and two-ply yarn is possible. Yarn diameter enlargement is not so significant and is maximally 8% of original diameter. Two-dimensional ANOVA analysis (factors: blending portion, plying) confirms that plying technology is a significant factor, which influences mechanical parameters \(F, e\), abrasion resistance \(a1\), \(a2\), and diameter change. Two-ply yarns made of 100%PP and 65PP/35CO are the best one in terms of strength, elongation, and abrasion resistance characteristics.

4. Conclusion

The main aim was to report about approaches to yarn resistance evaluation. Two sets of yarn were selected for experiment. Only the row of single and two-ply yarns was tested. The selected structure and mechanical parameters of fiber and yarn were analyzed. Zweigle G 552 was used for measuring yarn abrasion resistance. Number of strokes to yarn destruction and diameter change due to abrasion were observed. The generally known relationships were confirmed. Experimental results are in a good agreement with expectation. Increase of yarn count causes increase of yarn strength and abrasion resistance. Increase in number of twists is followed by increase of yarn strength and abrasion resistance. It is the reason of yarn elongation decrease. The influence of yarn count is in connection with number of fibers in yarn cross-section. Effect of twist is related to the level of fiber compactness. Two-ply yarn is more resistant to abrasion and is the reason of their using as warp yarn. Using of higher blending portion of a stiffer stronger component can improve yarn characteristics in terms of mechanical behavior and yarn abrasion. New approach to yarn abrasion evaluation was introduced. Interesting information was obtained thanks to comparison of yarn diameters before and after abrasion. Dimension of potentially thin and thick places is helpful for the assessment of weaving-ability. None of the parameters on its own provided a reliable method for establishing a definitive correlation between measurements made in laboratory and actual performance of yarns during weaving, because the process of mechanical yarn deformation on a loom is very complex and cannot be simulated absolutely during laboratory analysis.

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References


COMPUTED MICROTMOTOGY IN THE ANALYSIS OF FIBER MIGRATION IN YARN

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Abstract:

This study is a short analysis of the use of computer microphotography in fiber migration testing as a modern non-destructive testing method. Microtomography operates similarly to X-ray computed tomography systems used in medicine, but with much better resolution owing to the use of a smaller radiation spot. The internal structure is reconstructed as a series of two-dimensional cross-sections that are then used to create 2D and 3D morphological objects. This process is non-destructive and does not require special preparation of a testing material.

Keywords:

Computed tomography, Microtomography, Yarn structure

Introduction

X-ray computed tomography (CT) is a medical imaging method using computer processing of obtained images (scans). Digital processing of geometry is used to create three-dimensional (3D) image inside the object from large series of two-dimensional x-ray images taken around one axis. Although the computed tomography is most often used in medicine, it is also more and more often used for testing in materials engineering. Another example is the use of CT in archaeology for imaging of sarcophagus content or e.g. DigiMorph project of the University of Texas at Austin that uses a CT scanner to study biological and paleontological specimens. X-ray tomography offers a powerful tool that enables internal structure of textiles to be explored before and after deformation and provides information on their geometry.

Computed Tomography

Using a high resolution CT scanner is a non-destructive technique that may be used to obtain internal images of materials. Schematic operation principle is presented in Figure 1. An X-ray beam passing through a rotating sample gives a two-dimensional projection that is recorded by the CCD detector. The purpose of the detector scintillator (for example monocrystal of cadmium) is to convert the x-ray energy into visible light to protect CCD matrix against radiation. In classical tomography, 2D projection is made up of attenuation coefficients of each stage of object scanning. Data collected are then used for numerical volume reconstruction by using an algorithm filtering out rear projection. As a final result, 3D model is obtained [1].

Industrial CT

Industrial computed tomography is a process that uses X-ray equipment to produce a 3D model of components both in outer and internal structure. Industrial CT has already been used in many areas of industry to monitor internal components. The conversion of CT data into CAD models by using tools available on market is still quite difficult, and therefore this area offers large potential of development. In future, 3D-CAD rendering of data series from 3D tomography for simulation and analysis with the finite element method will be even more important. The reason for this is the fact that 3D model instead of theoretical model will be used as a basis for calculations for geometry of objects [2].
Materials and methods

Tests of five samples of multiple threads with a length of 5 mm were performed. Measurements of thread microtomography were taken with the best possible resolution of 2.5 µm. X-ray computed tomography is a non-destructive testing method of materials that makes it possible to obtain flat or spatial distribution of the selected physical quantity. It utilizes object projections taken from different directions to produce 2D sectional images or 3D spatial images. As a result of measurements, precise images of internal details of an object tested are obtained. Image scanning was performed by using SkyScan 1174 micro-CT scanner. An example 3D model of the sample D5 (1100 twists/m) is presented in Figure 3.

Results

As a result of imaging with CT, a set of images (scans) of the yarn cross-sections was obtained for each yarn sample as a bitmap that was then assembled into 3D model. Figures 4 - 8 present yarn in a longitudinal section for seven different distances from the yarn axis.

Discussions

As a result of CT scanning analysis of cotton yarn, it was found that the regularity of fiber distribution in section increases with increasing the number of yarn twists. Packing density of fibers across the yarn cross-section is different depending on the distance of section from the yarn axis. Considering the helical arrangement of fibers in yarn, it was found that fibers, in the core area, are in a straightened form or twisted one with a small helix radius. The fibers, located further from the yarn axis, increase helix radius r and relocate toward the outer surface.

As a result of scanning analysis of the samples of obtained yarns made of staple fibers, it was found that the regularity of fiber distribution in section increases with increasing the number of yarn twists. Packing density of fibers in the yarn longitudinal sections is different depending on the distance of section from the yarn axis. Considering the helical arrangement of fibers, it can be observed that the fibers are not uniformly distributed across the yarn cross-section. The packing density of fibers is different in the core area and between the core and the outer surface. This phenomenon is related to the tension of component fibers in the yarn twisting process.

The yarn structure is described by three main parameters: twist, fiber density, and fiber migration. The yarn structure may be divided into areas with larger or smaller radial coordinate. Packing density of fibers across the yarn cross-section is different. Its significant reduction occurs rather on the outer surface and in the core than between those areas. So far, the idealized helical yarn geometry according to Hearle J.W.S. theory (Figure 2a) has been taken in theoretical assumptions. In this theoretical model, it is assumed that yarn is of circular section and fibers form helical trajectories around the concentric cylinders with constant radius. Each fiber has a helical trajectory with constant pitch h and radius r, and helix angle increasing from 0 for r=0 to α for r=R. In reality, fiber trajectories in yarn are of very complicated shapes; one of such trajectories is shown in Figure 2b. Therefore, a fiber trajectory is often questionable [6,7].

Figure 2. a) Idealized twisted yarn geometry [7]; b) fiber trajectory in yarn [6]
Figure 3. An example of a three-dimensional model of the sample D5 – 1100 twist/m

Figure 4. The longitudinal section yarn in seven different distances from the axis of the yarn - cotton yarn 25tex, 700 twist/m

Figure 5. The longitudinal section yarn in seven different distances from the axis of the yarn - cotton yarn 25tex, 800 twist/m
Figure 6. The longitudinal section yarn in seven different distances from the axis of the yarn - cotton yarn 25tex, 900 twist/m

Figure 7. The longitudinal section yarn in seven different distances from the axis of the yarn - cotton yarn 25tex, 1000 twist/m

Figure 8. The longitudinal section yarn in seven different distances from the axis of the yarn - cotton yarn 25tex, 1100 twist/m
of fibers in yarn, it was found that fibers, in the core area, are in a straightened form and/or twisted one with a small helix radius and their uniform distribution. The fibers, located further from the yarn axis, increase their helix radius and are pushed toward the outer surface of the yarn.

**Conclusion**

There are many advantages to using CT scanning over traditional. The main points include:

- A non-destructive test for inspection and metrology;
- Design requirements for both internal and external components are validated quickly and accurately. Development costs are reduced in creating the first CAD model;
- Product quality is improved to reduce the risk of recalls;
- Internal complex features can be precisely measured without destructive testing;
- Parts are scanned in a free state environment with no fixtureing applying stresses which could damage delicate part or display warping that is not present in the part;
- For the first time rapid prototyping of the internal components can be completed without the daunting task of creating the CAD file from scratch.

**References**


