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# Surface Roughness Assessment of Woven Fabrics Using Fringe Projection Moiré Techniques

**Abstract**
*In this paper, a new approach is proposed for characterizing the surface roughness of woven fabrics. This approach is based on the fringe projection moiré techniques and analysis of the moiré pattern, which is caused by the interaction between the Ronchi grating and the periodic structure of a woven fabric. In this study, an image processing procedure was employed and a new parameter called the "roughness index" was defined for quantifying the surface roughness. The results obtained from the moiré technique were validated by a set of pair-comparison subjective tests. The proper correlation, with an average R-squared value of 0.9087, between subjective and objective tests confirmed the accuracy, correctness and efficiency of the new method. Statistical analysis of the roughness results clarified that the effect of fabric structural parameters such as the weave structure and weft density is significant in the confidence range of 95%.*

**Key words:** *surface roughness, moiré, fringe projection, image processing, pair-comparison test, fabric structure.*

## Introduction

The surface roughness influences the fabric hand and aesthetic properties and plays a significant role in the final use of the fabric. There are many testing methods that are used for the objective evaluation of the surface roughness in woven fabrics. These techniques can be divided into two categories: contact methods and non-contact methods. In the contact methods, surface devices such as tribometers are often used, providing information about the surface roughness of fabrics. Some of them work based on the principle of a "blade-disc" type tribometer. The sensor developed is a preloaded thin blade that vibrates when rubbed on a surface [1, 2]. Another example is the Kawabata evaluation system (KES), where the surface height variation trace is obtained. In this contribution, a simple technique based on the tracking of a metal blade on the textile surface and registration of the load required is described. Data obtained from the KES-FB4 instrument were subjected to digital signal processing techniques in order to get the spectral characteristics of the geometrical roughness measurements [3, 4]. Continuous recording of the load can also be realised on a TIRATEST tensile testing machine. The result of measurements is the surface force trace (SFV) [5]. A glove-type measurement system was also used with pressure sensors to investigate the characteristics of finger motion while evaluating the hand of a cloth. Through this system, it was observed that subjects used specific characteristics of finger motion when they evaluated the hand of cloth to determine resilience and roughness, and subjects could easily understand how to evaluate roughness and resilience [6, 7]. In the contact methods, due to the flexibility and vulnerable nature of textiles and since there is always a possibility for surface damage or change in the surface structure, many researchers have turned their efforts to proposing and demonstrating non-contact methods for measuring and analysing the surface roughness of fabrics. In this field of research, many devices and techniques have been utilised. The state of the fabric surface was studied by an optical multi-directional roughness meter with signal processing in a frequency domain in [8, 9], a wavelet-fractal method established to calculate the fractal dimension in order to objectively evaluate the surface roughness of fabric in [10, 11], and a device described which scans the surface with a laser line and performs a temporal Fourier analysis of the reflected light in [12-14]. The RCM device is another method in which the special arrangements of textile which bend around the sharp edge are used for obtaining the roughness profile in the direction selected (on the line transect of the surface). Image analysis is used for extraction of the surface profile. In another study, a sequence of silhouette images of textile surface patches was digitised progressively, where a sample was passed through the sharp edge of a cross-beam in a bending state so that the whole 3D surface profile could be generated by a combination of the silhouette height profile of each surface patch in the sequence [15,16]. Other non-contact methods known are the laser triangulation method [17,18], the confocal microscope [19, 20], and interferometric profilometers, which allow the user to determine the profile of the surface. In this method, a laser beam is split into a part which goes on the fabric and the other which goes on a fixed mirror. The difference in the optical path between the two beams generates interferential fringes. The number of fringes is proportional to the optical path difference. As the position of the mirror is known, the altitude of the surface point can be obtained. Methods based on the projection of fringes [21] or speckle [22] on the surface are also used to obtain information about the roughness of the surface and then the fringe patterns are obtained and analysed by image processing [23].

Considering the researches mentioned above, it was observed that there is still a requirement for proposing accurate, straightforward and less time consuming methods for measurement of fabric surface roughness. Thus, in this study a novel objective method which uses the moiré fringe projection technique is presented to accurately characterise the surface roughness of woven fabrics. The data obtained from this method are validated by a set of subjective pair-comparison tests. In the end, the effect of fabric structural parameters on the surface roughness of woven fabrics is investigated.

## Theoretical approach

### Theoretical background for moiré techniques

The word "moiré" comes from the name of a silk fabric which, when folded, exhibits patterns of light and dark bands. Moiré is a similar effect to light and dark bands, or "fringes", produced by the superposition of two sets of gratings when certain circumstances required are satisfied [24]. In optics, the term "moiré" refers to a beat pattern produced between two gratings of approximately equal spacing [25]. Thus moiré techniques are based on the effect of the superposition of grating lines. Such grating lines might be physical transparencies or periodic variations of the reflectance of a surface, or they might be formed by interference between two light waves (projected on a surface). This technique can be applied for optical testing such as that of aspheric surfaces, measurements of surface roughness, form measurement, measurement of deformation and strain, as well as analysis of vibrations and flows [26-27]. The moiré pattern, which is caused by the superposition of two similar gratings, is shown in ***Figure 1***.

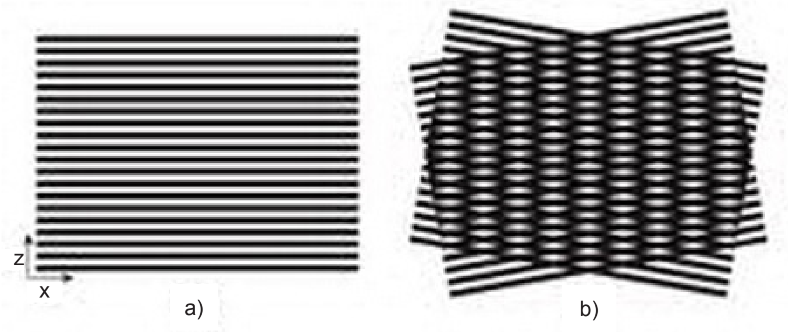


***Figure 1.*** *Moiré pattern resulting from the overlapping of two similar gratings.*

### *Theoretical background for fabric surface roughness using moiré techniques*

Moiré techniques are based on the effect of the superposition of grating lines. Such grating lines might be physical transparencies (in our case a Ronchi grating with 5 lines/mm frequency) or periodic variations of a surface (in our case the periodic structure of the fabric surface). A schematic of the overlapping of a Ronchi grating on fabric is shown in ***Figure 2***.

In this study, horizontal grating lines are projected on a fabric so they interfere with weft yarns in the same direction, with the resultant moiré pattern appearing in the vertical direction. The moiré pattern mentioned is only visible when the density of grating lines and the fabric's weft density become similar. In this situation, the properties of the moiré pattern such as the number of moiré lines, their thickness and area are affected by fabric surface properties. In this work, the relation between fabric surface roughness and characteristics of the resulting moiré pattern are investigated. Finally the results obtained are validated by a set of subjective pair comparison tests using the Thurstone method.

## Thurstone's paired-comparison method

Given a collection of n objects, the method of paired-comparisons consists of preparing pairs of objects, and for each pair obtaining one or more judgments as to which member of the pair exceeds the other with regard to some attribute. The law of comparative judgment which was proposed by Thurstone attempts to account for the resulting judgments in terms of n random variables, $X_1$, $X_2$... $X_n$. Whenever a comparison between objects i and j is required, a sample is drawn from these random variables and object i is judged to be above or below object j according to whether the sampled value of $X_i$ is greater or less than the sampled value of $X_j$. Various formulations of the law of comparative judgment differ in the distributional assumptions made about $X_i$. If we indicate the probability that object i will be judged 'less than' object j by the symbol $\pi_{ij}$, the law of comparative judgment states that:

$$\pi_{ij} = P\ (X_i < X_j) \qquad (1)$$

$$\mu_i = \xi\ (X_i)\ (1 \le i \le n) \qquad (2)$$

$$\sigma_{i2} = \sigma\ x_{i2}\ (1 \le i \le n) \qquad (3)$$

$$r_{ij} = rx_ix_j\ (1 \le j \le i \le n) \qquad (4)$$

The random variable, $X_i$ - $X_j$, has an expected value of $\mu_i$ - $\mu_j$ and a variance of a $d_{ij2} = \sigma_{i2} + \sigma_{j2} - 2\ r_{ij}\sigma_i\sigma_j$. Consequently,

$$Z_{ij} = (X_i - X_j - \mu_i + \mu_j)/d_{ij} \qquad (5)$$

If the assumption is made that each $Z_{ij}$ has the probability density function $\psi(x)$, where the corresponding cumulative distribution function is,

$$\psi(x) = \int_{-\infty}^{x} \Psi(z)dz \qquad (6)$$

The law of comparative judgment can be written as:

$$\pi_{ij} = P(X_i - X_j < 0) = P\left(\frac{Xi - Xj - \mu i + \mu j}{dij} < \frac{\mu i - \mu j}{dij}\right) = \qquad (7)$$
$$= \Psi\left(\frac{\mu i - \mu j}{dij}\right)$$

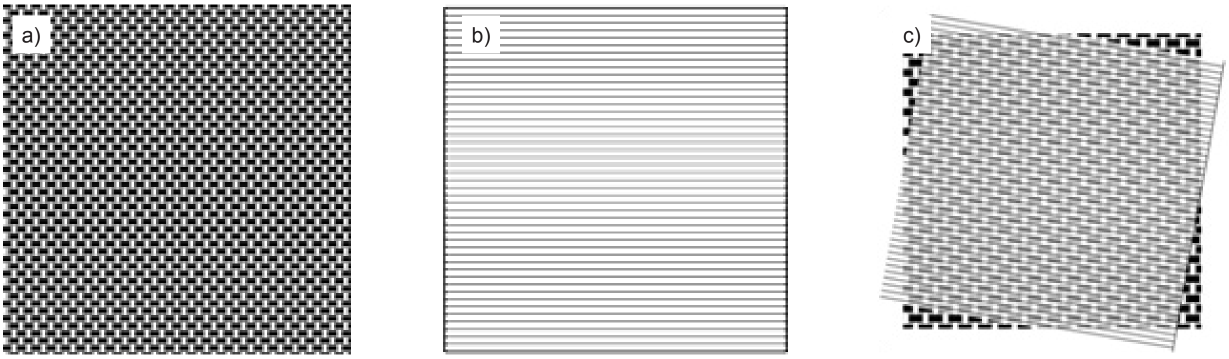


***Figure 2.*** *Overlapping of a Ronchi grating on fabric; a) fabric, b) ronchi grating, c) overlapping of grating on fabric.*

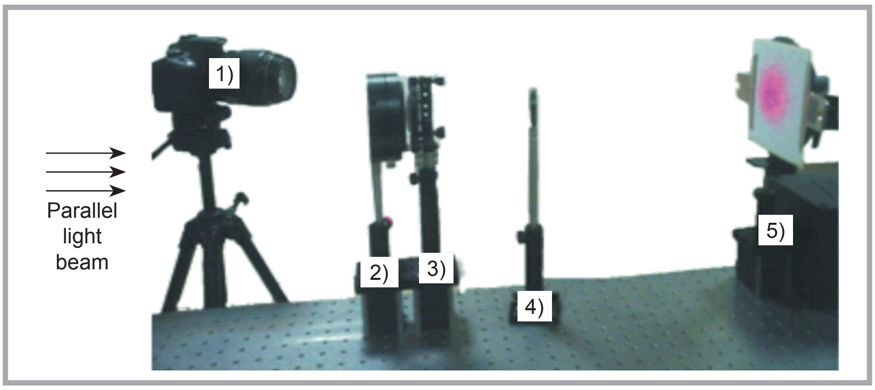


***Figure 3.*** *Experimental set up: 1) camera, 2) Ronchi grating, 3) achromatic lens 4) pin hole, 5) fabric.*

The method mentioned can be used for obtaining a perceptual (scaling) for defining a specific property such as roughness [28 - 30]. The pair-wise responses are experimental data achieved by asking the subject how they feel about the sense of roughness of the two fabric pairs at a time. Each subject is asked to independently give his/her opinion as to which of the two fabrics is the rougher in a pair. Thus the method mentioned is utilised to scale the relative differences of roughness from among a set of fabric pairs.

***Table 1.*** *Fabric characteristics.*

| Fabric code | Weave structure | Density, cm$^{-1}$ | |
|---|---|---|---|
| | | Warp | Weft |
| F1 | Plain | 48 | 22 |
| F2 | | | 25 |
| F3 | | | 28 |
| F4 | | | 31 |
| F5 | | | 34 |
| F6 | Twill 3/1 | | 22 |
| F7 | | | 25 |
| F8 | | | 28 |
| F9 | | | 31 |
| F10 | | | 34 |
| F11 | Twill 3/3 | | 22 |
| F12 | | | 25 |
| F13 | | | 28 |
| F14 | | | 31 |
| F15 | | | 34 |
| F16 | Twill 2/2 | | 22 |
| F17 | | | 25 |
| F18 | | | 28 |
| F19 | | | 31 |
| F20 | | | 34 |
| F21 | Twill 2/1 | | 22 |
| F22 | | | 25 |
| F23 | | | 28 |
| F24 | | | 31 |
| F25 | | | 34 |

## Experimental

### *Investigated fabrics*

The aim of this research was to study the surface roughness of woven fabrics, hence requiring to produce a set of woven fabrics with a variety of surface roughness. In this study, twenty five groups of woven fabrics were used for the measurement of this property. As the structural parameters of the woven fabrics affect the roughness, these fabrics consisted of five different weave structures with five various weft densities. Detailed information of the fabrics is gathered in ***Table 1***. It should be noted that both warp and weft densities can influence the roughness, thus it was decided to keep the warp density constant and only change the weft density and weave pattern. It should be emphasised that the combination of the weave structure and weft density can affect the position and arrangement of yarns, yarn crimp, fabric shrinkage and … in each group of fabrics, and could obviously alter the surface roughness. The fabrics were woven in a real production environment on a loom with desired specifications.

### Experimental set-up and sample preparation

The set up used for experiments is shown in ***Figure 3***. This set up consists of a light source, which in our case was a helium-neon laser beam. The helium-neon laser is a red beam at 632.8 nm with a cw (continuous wave form) output ranging from 1 to 100 mW. The laser should produce an intense, concentrated and highly parallel beam of coherent light in order to obtain accurate results.

This laser beam passed through a mirror and then a spatial filter including focusing lens and a pin hole. The beams were paralleled and strengthened by passing through a collimating lens. The next part was Ronchi grating at a frequency of 5 lines/mm, selected considering the fineness of the surface investigated. In case the surface becomes finer, the density of printed lines in a unit length should increase. For the range of fabrics used in this research, grating at a frequency of 5 lines/mm is suitable. The grating lines produced in this section were amplified by an achromatic lens (AC 508-250A) which was set as close as possible to the grating. In the next section, a pin hole was used for controlling the passage of the strongest light beam and its projection on the sample (fabric). Finally after the projection of grating lines and their superposition with the fabric, the resultant moiré patterns were captured by a digital camera (Canon EOS-350D).

It should be noted that choosing the appropriate elements for the set up and precise adjustment of its different components, especially the light source illumination evenness, is crucial for achieving repeatable, correct and reliable data. Finally fabric samples were prepared with dimensions of 12 × 12 cm, attached to a black cardboard to prevent light passage through the fabric, and positioned on a special pedestal.

### Assessment of surface roughness using the moiré technique

In the current test, it can be claimed that the moiré pattern is in fact the interaction between the fabric and grating. One of the requirements for producing the moiré effect (specific fringe pattern) between these two periodic patterns is that the frequencies of the grating pattern and fabric (yarn density) must be the same. This specific pattern is visible in ***Figure 4***. In order to have similar frequencies for the

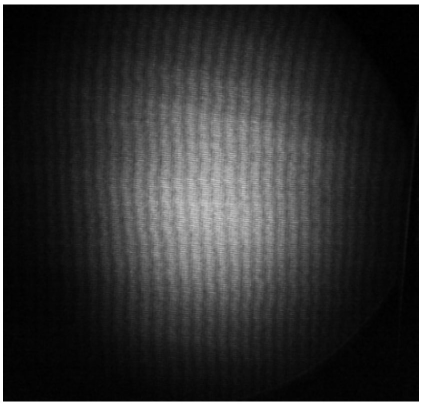


***Figure 4.*** *Specific moiré pattern desired.*

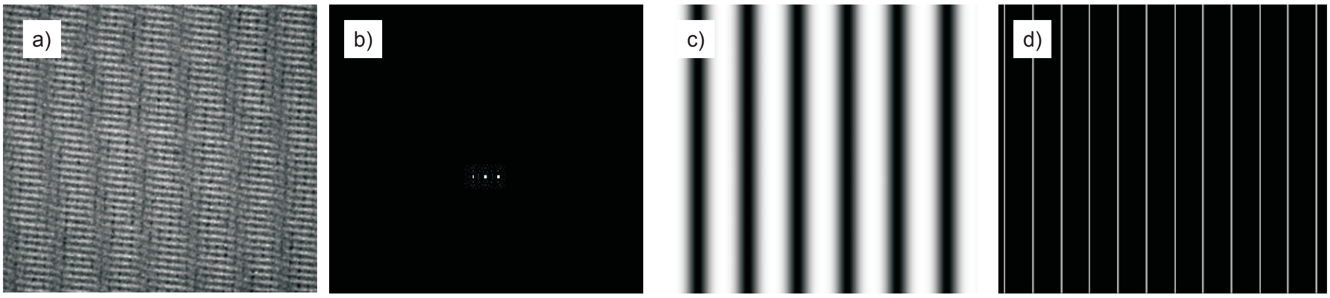


***Figure 5.*** *Image processing procedure for moiré line counting; a) original moiré image, b) filtered Fourier spectrum, c) reconstructed image, d) Canny edge detection.*

grating pattern and fabric, the distance between the Ronchi grating (5 lines/mm) and fabric should vary. By changing the distance between the Ronchi grating and fabric, the number of grating lines projected on the fabric surface in a unit length differs. In case the density of the grating lines projected and density of the fabric becomes too close to each other in an identical direction, a small rotation of the Ronchi grating (less than 10 degrees) can cause the moiré pattern desired, produced by the superposition of Ronchi grating lines and fabric yarns (periodic structure of fabric), which is clear in ***Figure 4***.

The distance between the Ronchi grating and fabric in which the moiré pattern desired is achieved was experimentally found for various fabrics. The distance measured for different samples is shown in ***Table 2***.

As is clear in ***Table 2***, the distance between the grating and fabric measured is nearly the same for fabrics with similar weft densities. Thus it can be claimed that this distance is in accordance with the weft density of the fabrics tested.

Finally after obtaining the proper moiré pattern, an image was captured using a digital camera. It should be noted that the camera was set as close as possible to the fabric, at the same height but at a 30° inclination to the fabric. The position of the camera, light source, illuminating components and fabric remained constant for all sample groups. The Ronchi grating was the only movable element during the roughness tests.

The image captured was then fed to an image processing procedure for acquiring the parameters desired from the moiré pattern related to the surface roughness of the fabric.

### Image processing procedure in Matlab

It was preliminarily necessary to prepare the captured image for precise measurement of moiré parameters. A square of 4 × 4 cm size was cropped from the center of the image captured. The contrast of the image was adjusted to improve its quality and then by using the threshold function, various intensities over the image were identified. In the next step, the number of moiré lines was counted using the Fourier transform. The output of the transformation represents the image in the frequency domain, in which each point shows a particular frequency contained in the spatial domain image. The Fourier transform theorem can be stated in one or multiple dimensions depending on the number of independent variables used in the function transformed. If a function f(x) in the time (or spatial) domain is known, its one dimensional Fourier transform F(u) is defined as,

$$F(u) = \int_{-\infty}^{\infty} f(x) e^{-j2\pi ux} \, dx \qquad (8)$$

where, u is the variable frequency and $j = \sqrt{-1}$.

After this stage, unrelated peaks in the Fourier spectrum were filtered and the image was reconstructed utilising the inverse Fourier transformation. Then the Canny edge detector function was used to identify the moiré lines. The Canny function finds edges by using derivatives of the Gaussian filter. The method uses two thresholds to detect strong and weak edges. The procedure for this part of the image processing is shown in ***Figure 5***. Each of the two lines in ***Figure 5.d*** represents a moiré line, and hence by counting them it is possible to have the number of moiré lines.

In the next step, another image processing procedure was followed to measure the area of moiré lines for each group of fabrics. In this part of the work, the quality of the image was initially improved and then converted to an inverse binary image, filtered by the median function. In order to have continuous fringes in the vertical direction, a set of morphological operations was used. Finally the area of moiré fringes was cumulatively calculated. Different stages of the procedure are shown in ***Figure 6*** (see page 80).

### Roughness data acquisition

The number of moiré lines for fabrics of similar weft density is the same, but varies for different weft densities. By increasing the weft density of the fabric, the number of moiré lines rises. The area of moiré lines in a specific region of the image captured was calculated by the procedure mentioned in the previous section. In order to normalise the area cal-

***Table 2.*** *Distance between Ronchi grating and fabric.*

| Fabric code | Weave structure | Density, cm$^{-1}$ | | Distance between grating and fabric, cm |
|---|---|---|---|---|
| | | Warp | Weft | |
| F1 | Plain | 48 | 22 | 53.5 |
| F2 | | 48 | 25 | 47.5 |
| F3 | | 48 | 28 | 43.5 |
| F4 | | 48 | 31 | 40.5 |
| F5 | | 48 | 34 | 38.3 |
| F6 | Twill 3/1 | 48 | 22 | 53.5 |
| F7 | | 48 | 25 | 47.5 |
| F8 | | 48 | 28 | 43.5 |
| F9 | | 48 | 31 | 40.5 |
| F10 | | 48 | 34 | 39.0 |
| F11 | Twill 3/3 | 48 | 22 | 53.5 |
| F12 | | 48 | 25 | 47.5 |
| F13 | | 48 | 28 | 43.5 |
| F14 | | 48 | 31 | 41.0 |
| F15 | | 48 | 34 | 38.5 |
| F16 | Twill 2/2 | 48 | 22 | 53.5 |
| F17 | | 48 | 25 | 47.5 |
| F18 | | 48 | 28 | 43.5 |
| F19 | | 48 | 31 | 41.0 |
| F20 | | 48 | 34 | 39.0 |
| F21 | Twill 2/1 | 48 | 22 | 52.8 |
| F22 | | 48 | 25 | 47.5 |
| F23 | | 48 | 28 | 43.5 |
| F24 | | 48 | 31 | 40.6 |
| F25 | | 48 | 34 | 39.2 |

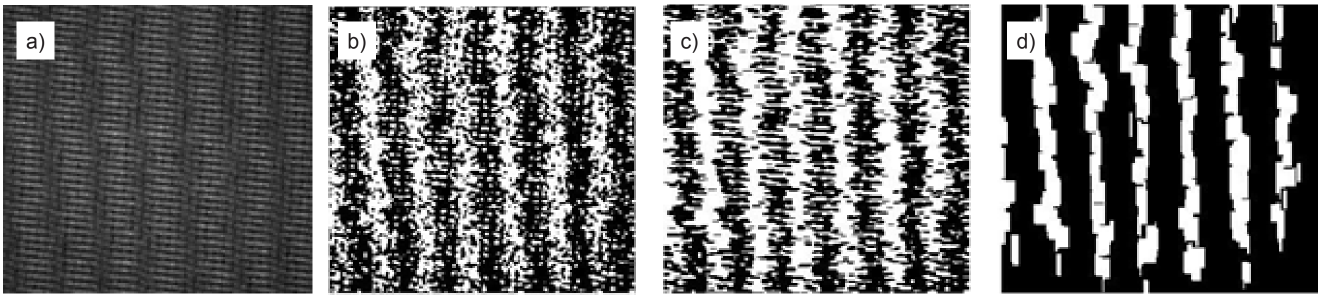


***Figure 6.*** *Image processing procedure for measuring the area of moiré fringes; a) original moiré image, b) inversed binary image, c) filtered image, d) moiré fringes.*

culated, the area measured was divided by the number of moiré lines; thus it was possible to have the area of the moiré pattern per line, and in this way the calculation errors diminished. This factor was used as an indicator of the surface roughness of the fabrics, called the "roughness index", and found to be a proper indicator and quantifier of fabric surface roughness.

### Subjective evaluation of surface roughness by the Thurstone method

In this study, a set of subjective tests for evaluation of fabric surface roughness was carried out. The results obtained from them were used to validate the roughness results achieved from moiré tests, for which Thurstone's pair comparison method was employed. A group of 15 textile experts familiar with fabric structure, both men and women of different ages (22 - 50 years), were asked to take part in the subjective evaluation of fabrics.

In the pair comparison method, each sample is paired with others in all possible states. In this way, if the number of samples is n, in each set of the experiments the subject evaluates n(n - 1)/2 pairs. Fabric specimens with dimensions of 12 × 12 cm were attached to cardboard. In each section of the experiment, a pair of specimens was randomly put in front of a subject whose eyes were closed. The subject was asked to touch the fabric in an upside down path and announce the rougher specimen in a pair. After the recording of data, the "roughness scale value" for various sample groups was estimated. The scale value defines the location and distance between different samples.

| | 1 | 2 | … | k | … | N |
|---|---|---|---|---|---|---|
| **1** | ---- | $f_{12}$ | | $f_{1k}$ | | $f_{1n}$ |
| **2** | | ---- | | | | |
| **…** | | | | | | |
| **j** | $f_{j1}$ | $f_{j2}$ | | $f_{jk}$ | | $f_{jn}$ |
| **…** | | | | | | |
| **n** | $f_{n1}$ | $f_{n2}$ | | $f_{nk}$ | | ---- |

***Figure 7.*** *Matrix F.*

In order to calculate the scale value, three different matrixes should be formed. Matrix F is an n×n matrix, where n is the number of samples. Each array $f_{jk}$ shows the number of times that sample k was detected as being rougher than sample j. The total form of matrix F is as ***Figure 7***:

Then the arrays of matrix P are calculated by dividing those of F by the number of subjects. The arrays of matrix X are found from matrix p and using the normal distribution table. Finally the scale values are estimated by the following equation:

$$\begin{gathered} s_1=0 \\ s_2=d_{12} \\ s_3=s_2+d_{23} \\ \ldots. \\ s_n=s_{n-1}+d_{n-1,n} \end{gathered} \tag{9}$$

where, $d_{n-1,\,n} = x_n - x_{n-1}$

## Results and discussion

### Roughness measurement results

The results obtained for the roughness index measured using the fringe projection method are shown in ***Table 3***. For the set of fabrics which were used in this study, the value of the roughness index varies in the range of 1491 for the fabric with the lowest roughness value, to 4965 for the roughest fabric.

Values of the roughness index for different weft densities and weave structures show a special trend which will be discussed in the next sections.

In order to analyse the concluded data statistically, SPSS software was used. The results revealed that at the confidence range of 95%, the effect of the weft density and weave structure is significant for the surface roughness of woven fabrics.

### Subjective surface roughness evaluation results

The data collected from the subjective tests were gathered and by applying the procedure which was presented above, the roughness scale value for various weave structures was calculated. The roughness trend for various weave structures is plotted in ***Figure 8***. As is shown in ***Table 1***, in this study five groups of weave structures with five different weft densities were used. Since the trend of

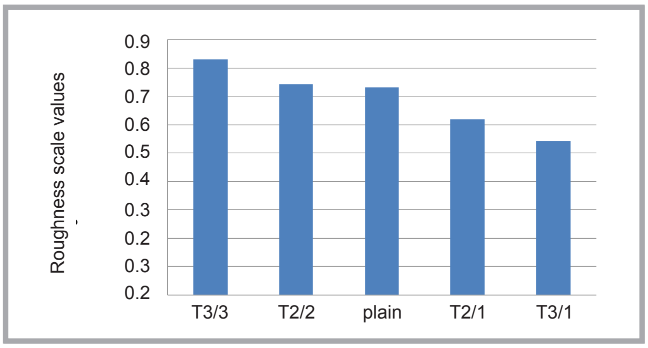
***Table 3.*** *Roughness index results for various samples.*

| Fabric code | Weave structure | Density, cm$^{-1}$ | | Roughness index |
|---|---|---|---|---|
| | | Warp | Weft | |
| F1 | Plain | 48 | 22 | 4382.0 |
| F2 | | 48 | 25 | 3341.6 |
| F3 | | 48 | 28 | 2869.3 |
| F4 | | 48 | 31 | 2865.5 |
| F5 | | 48 | 34 | 1844.3 |
| F6 | Twill 3/1 | 48 | 22 | 3855.3 |
| F7 | | 48 | 25 | 3141.1 |
| F8 | | 48 | 28 | 2091.6 |
| F9 | | 48 | 31 | 1659.7 |
| F10 | | 48 | 34 | 1491.4 |
| F11 | Twill 3/3 | 48 | 22 | 4964.9 |
| F12 | | 48 | 25 | 3936.8 |
| F13 | | 48 | 28 | 3531.2 |
| F14 | | 48 | 31 | 3289.9 |
| F15 | | 48 | 34 | 2006.0 |
| F16 | Twill 2/2 | 48 | 22 | 4583.2 |
| F17 | | 48 | 25 | 3442.6 |
| F18 | | 48 | 28 | 3305.7 |
| F19 | | 48 | 31 | 2937.8 |
| F20 | | 48 | 34 | 1879.3 |
| F21 | Twill 2/1 | 48 | 22 | 4123.6 |
| F22 | | 48 | 25 | 3194.0 |
| F23 | | 48 | 28 | 2387.4 |
| F24 | | 48 | 31 | 2076.3 |
| F25 | | 48 | 34 | 1809.9 |

scale values for all weave patterns with various weft densities was similar, the average scale value for different densities was reported for each weave structure (***Figure 8***).

According to subjective tests, among the different weave structures, twill 3/3 had the highest roughness value, while twill 3/1 was the smoothest fabric. The roughness feeling perceived from plain and twill 2/2 was close to each other but twill 2/2 had a higher roughness value.

***Figure 8.*** *Roughness scale values for different weave structures.*



### Correlation between the results obtained from the moiré technique and subjective method

In this part, the results which were achieved from subjective tests (roughness scale value) were used to check the validation of values of the roughness index determined from moiré tests. Moreover the correlation between the "subjective roughness scale values" and "roughness index" for various patterns was analysed. As is clear from ***Figure 9***, there is an adequate correlation (R-squared value in the range of 0.7933 to 0.9892) between the results of both subjective and objective assessments.

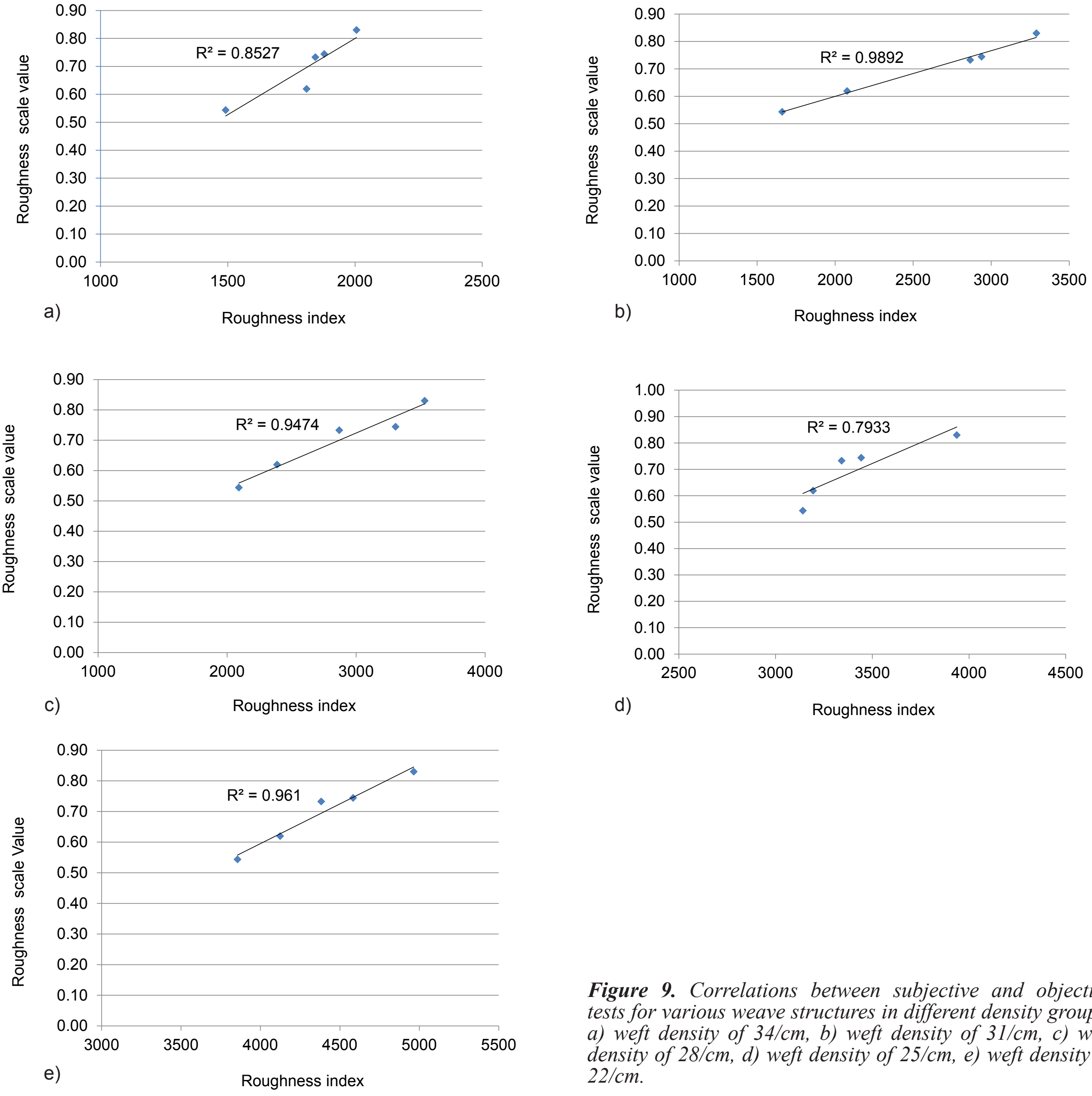


***Figure 9.*** *Correlations between subjective and objective tests for various weave structures in different density groups; a) weft density of 34/cm, b) weft density of 31/cm, c) weft density of 28/cm, d) weft density of 25/cm, e) weft density of 22/cm.*

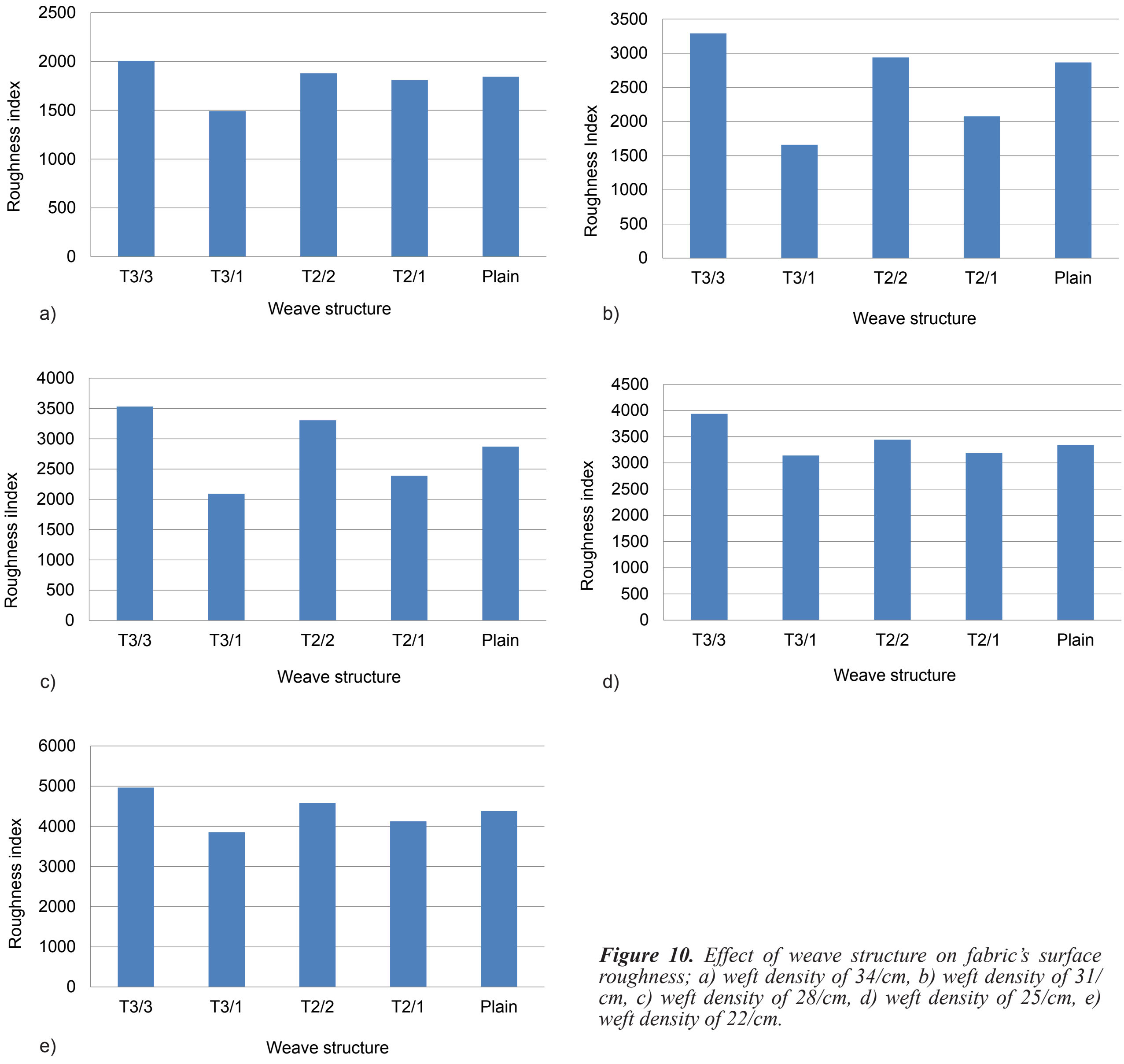


***Figure 10.*** *Effect of weave structure on fabric's surface roughness; a) weft density of 34/cm, b) weft density of 31/cm, c) weft density of 28/cm, d) weft density of 25/cm, e) weft density of 22/cm.*

Considering the R-squared values shown in ***Figure 9***, it is possible to claim that the innovative method introduced for the measurement of fabric surface roughness is reliable and can be used for rapid and accurate evaluation of the surface roughness of woven fabrics. In other words, the moiré pattern, which is caused by interaction between the grating and fabric surface structure, is a proper indication of surface asperities and can be successfully used for evaluation of the surface roughness of woven fabrics.

### Effect of weave structure on fabric's surface roughness

Analysis of the roughness data was carried out in order to study the influence of the fabric weave structure on the surface roughness of the fabrics tested, in which a diagram of the roughness index for different weave structures was plotted. As is clear in ***Figure 10***, in all density groups, twill 3/3 had the highest value of roughness index. The roughness estimated for twill 2/2 was more than plain, while twill 2/1 was smoother than plain. Finally the lowest value for the roughness index was achieved for twill 3/1. Thus it can be concluded that twill 3/3 is the roughest and twill 3/1 the smoothest fabric, which is in accordance with the subjective tests.

### *Effect of weft density on fabric's surface roughness*

Roughness indexes proportional to the weft density of the fabrics were investigated. Analysis of results revealed that by increasing the weft density of the fabric, the value of the roughness index decreases and the surface of the fabric becomes smoother. As is shown in ***Figure 11***, this trend is observable in various weave structures.

By increasing the number of yarns in a similar unit length of the fabric, the gaps between yarns in the fabric structure reduces and the evenness of the fabric rises and the surface becomes smoother.

## Conclusions

In this study, a novel, rapid and accurate non-contact method for characterising the surface roughness of woven fabrics is presented. In the method introduced,

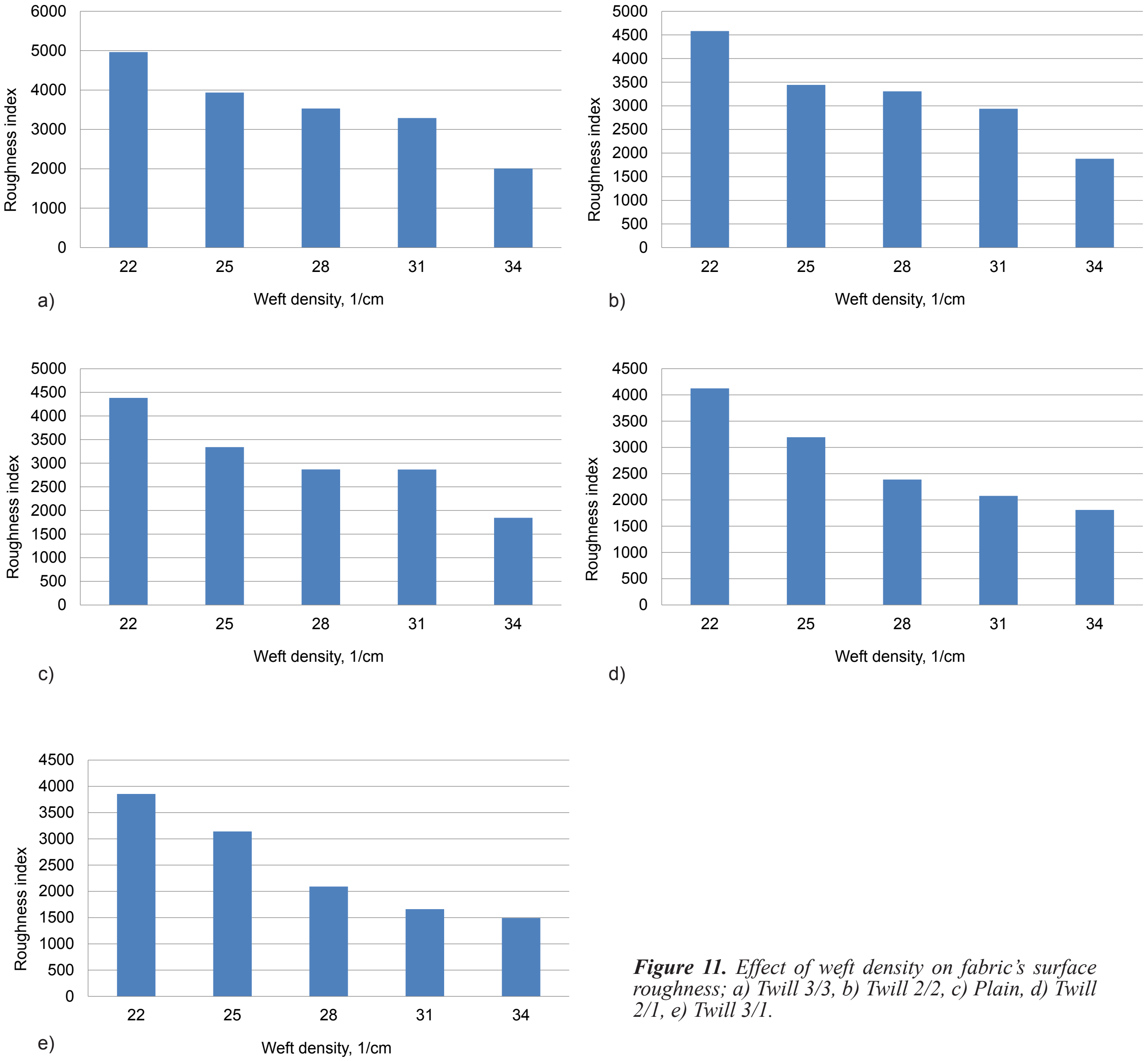


***Figure 11.*** *Effect of weft density on fabric's surface roughness; a) Twill 3/3, b) Twill 2/2, c) Plain, d) Twill 2/1, e) Twill 3/1.*

the fringe projection moiré technique is employed for measurement of surface roughness. This moiré pattern is the result of interaction between the Ronchi grating and periodic structure of the woven fabric, which is mainly affected by the surface characteristics of fabrics. In view of this, a new parameter known as the roughness index was derived from the moiré pattern. The validity of this parameter was tested by a set of subjective tests using Thurstone's pair-comparison method. There was a sufficient correlation between the subjective and roughness index results, which is testimony of the reliability of the new fringe projection moiré technique for evaluation of a fabric's surface roughness.

It should be noted that accurate adjustment of the testing set up, specifically the light source and position of the camera, is essential for achieving repeatable and precise data.

In addition, the significant benefit of this method is that it is suitable for measuring the surface roughness of a wide range of woven fabrics, with different colours, material and structures.

Analysis of the roughness results revealed that the effect of fabric structural parameters such as the weave structure and weft density is significant for the roughness at a confidence range of 95%. By increasing the weft density of fabrics, their surface roughness decreases. It was also observed that twill 3/3 had the roughest weave structure while twill 3/1 had the smoothest, which were in accordance with the subjective tests.

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