Indian Journal of Fibre & Textile Research
Vol. 42, March 2017, pp. 43-50

Modelling of surface roughness based on geometrical parameters of woven fabrics

Nazanin Ezazshahabi[1,a], Mohammad Amani Tehran[1], Masoud Latifi[1] & Khosro Madanipour[2]

[1] Department of Textile Engineering, Textile Excellence and Research Centers, Amirkabir University of Technology, Tehran, Iran
[2] Optical Measurement Laboratory and Optic Research Group, Amirkabir University of Technology, Tehran, Iran

Received 4 February 2015; revised received and accepted 1 June 2015

A novel model has been developed for the surface roughness evaluation of woven fabrics, based on fabric geometrical parameters. The model is developed based on the properties of twenty five groups of woven fabrics consisting of five various weave structures and five different weft densities. The output of the model is validated through a set of subjective roughness pair-comparison tests. The model output is found to be in accordance with the roughness scale value which is obtained from subjective tests, to a reasonable extent. The statistical analysis of roughness results shows that the effect of fabric structural parameters such as weave structure and weft density is significant in the confidence range of 95%. This model can be utilized for the prediction of the roughness behavior of various types of woven fabrics. Bearing in mind the influence of fabric surface roughness on the comfort and aesthetic properties of cloths, the usage of the model is a guide for selecting the suitable fabric for various end uses.

Keywords: Fabric geometry, Subjective evaluation, Surface roughness, Weave structure, Weft density, Woven fabric

1 Introduction

Surface roughness is an important property which influences the fabric hand, clothing comfort and aesthetic characteristics. The measurement, quantification and analysis of surface roughness have been the subject of many previous research works, due to the decisive role of these parameters in the selection of an appropriate fabric for different technical and clothing end-uses. Many studies have focused on the measurement of fabric surface roughness by objective and subjective methods. The evaluation of fabric surface roughness is possible by using either contact or non-contact methods. In this regard, many devices and techniques have been employed. In contact methods, surface measurement devices such as tribometers are often used. They provide information about the surface roughness of fabrics[1,2]. Another example is the Kawabata evaluation system (KES), where the surface height variation trace is obtained[3,4]. A glove-type measurement system was also used with pressure sensors to investigate the characteristics of finger motion while evaluating the roughness of a cloth[5, 6]. In the contact methods, due to the flexible nature of fabrics and since there is always a possibility for surface damage or change in the surface configuration, many researchers have tried to propose and reveal non-contact methods for measuring and analysing the surface roughness of fabrics. Non-contact methods can be listed as: (i) the RCM device[7], (ii) the laser triangulation method[8,9], (iii) confocal microscope[10,11], and (iv) interferometric profilometers which allow the user to determine the profile of the surface. Methods based on the projection of fringes[12] or speckle[13] on the surface are also used to obtain information about the roughness of the surface and then the fringe patterns are obtained and analyzed by image processing procedures[14]. The state of the fabric surface was also studied by an optical multi-directional roughness meter with signal processing in a frequency domain[15,16], a wavelet-fractal method to calculate the fractal dimension in order to objectively evaluate the surface roughness of fabric[17,18], and a device which scans the surface with a laser line and performs a temporal Fourier analysis of the reflected light[19-21].

In view of the studies mentioned above, it is apparent that most researchers focused on experimental methods for characterizing the surface roughness of fabrics and the lack of theoretical and modelling approaches for quantifying this property is obvious. Hence, it is intended to propose a model based on fabric geometrical factors for studying the surface roughness of woven fabrics.

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[a] Corresponding author.
E-mail: ezazshahabi@aut.ac.ir

By demonstrating this model, it is possible to identify the effective aspects of the structure of woven fabrics on surface roughness and also discover the way that they influence this property. Moreover, the significance of putting forward a model for predicting the surface roughness of woven fabrics is that the roughness properties of woven fabrics can be estimated without complex and time consuming experimental procedures, and even before the production of these fabrics. So with the aid of this model, the designers in the weaving looms have the ability to design a fabric with specific surface roughness, simply by applying changes in fabric structural parameters such as weave structure and yarn density.

In order to verify the strength and efficiency of the model, a set of subjective pair-comparison tests, using Thurstone's method are carried out to assess the surface roughness of the fabrics. Ultimately, after analyzing the correlation between the roughness scale values which is obtained from the subjective pair-comparison tests, and the output of the model, the effect of fabric structural parameters on the surface roughness of woven fabrics is investigated.

2 Materials and Methods

In this study, twenty-five groups of woven fabrics were used to assess their surface roughness subjectively. These fabrics consisted of five different weave structures with five various weft densities. All of them included 100% polyester filament yarns for warp and 100% cotton yarns for weft. The warp and weft yarn counts were 100 den and 30 Ne respectively. The detailed information of fabrics is given in Table 1.

The fabric samples were prepared with dimensions of 12×12 cm^2 and attached to a cardboard.

Table 1— Fabric characteristics
[Warp density 48 cm^{-1}]

Fabric code	Weave structure	Weft density, cm^{-1}
F1	Plain	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

2.1 Subjective Evaluation of Surface Roughness

Thurston pair comparison method was used for subjective evaluation of surface roughness. For a collection of *n* objects, the method of paired-comparison 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[22]. In this work, a set of subjective tests for evaluation of fabric surface roughness was carried out. The results obtained from subjective tests were used to validate the output of the surface roughness model (Rm). In this regard, a group of 15 textile experts, who were familiar with fabric structure, both men and women of different age groups (22-50 years), were asked to take part in the subjective evaluation of fabrics.

In the pair comparison method, each sample was paired with others in all possible states. In this way, if the number of samples is n, in each set of experiments the subject evaluates $[n(n-1)/2]$ pairs. 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 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[22].

2.2 Roughness Geometrical Model

The study presents the simplifying assumptions, definitions and on the whole various aspects of the proposed roughness model. In order to utilize this model, following four assumptions should be considered:

- Yarns are inextensible
- Yarns are incompressible
- The cross-section of yarns is regarded as a circle
- The effect of fabric hairiness is neglected

In the first stage, in order to propose the fabric geometrical model, the configuration of yarns in each repeat of the weave structure was studied. The aim of this consideration was to identify the effective factors on the surface roughness of fabrics .The simulation of each weave structure in a repeat of twelve yarns and the geometrical illustration for each yarn in a repeat is shown in Fig. 1.

Regarding the fabric simulation, it was found that there are 5 dominant factors which have a prominent role in evaluating the roughness behavior of woven fabrics. These parameters are given below:

(i) N — number of warp and weft interlacing points
(ii) L_d — non-floating length of yarn on fabric surface
(iii) K — number of yarns which are positioned in non-floating region
(iv) L_y — distance between yarns in non-floating region
(v) L_u/L_d— fraction of floating and non-floating length of yarn on fabric surface

It should be noted that in order to determine the mentioned parameters under an equal condition, all calculations were carried out in a specified length of 10 cm of fabric (Table 2). These parameters were calculated for all sample groups and then the results were normalized to locate the data between 0 and 1. In this regard, in order to normalize each of the mentioned parameters, following equation was utilized:

$$\frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad \dots (1)$$

where X is the value achieved for each factor; $X_{\min,}$ the minimum value obtained for each parameter; and $X_{\max}$, the maximum calculated value for each factor.

The analysis of the covariance of the detected influencing geometrical parameters revealed that all these are independent from each other and can individually play a significant role in the model.

Among the various models used to find out the structure of the roughness model, it was found that the linear backward regression model can properly exhibit the roughness behavior of the woven fabrics. The output of the model is named "Rm" which indicates the roughness estimations which are achieved from the model. The equation of the presented roughness model is given below:

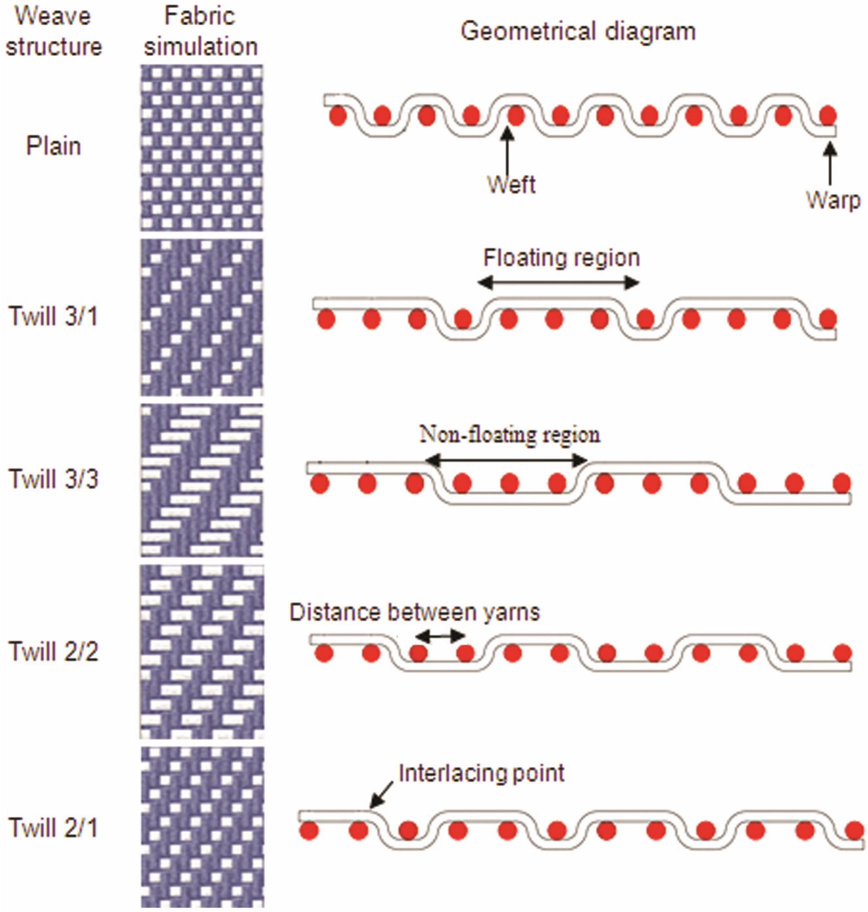

Fig.1— Fabric simulatuion and geometrical diagram

$$Rm = A_0 + A_1 \times N + A_2 \times L_d + A_3 \ \ K + A_4 \times Ly + A_5 \times \left(\frac{Lu}{Ld}\right) \quad \ldots (2)$$

In order to determine the values of coefficients $A_0, \ldots, A_5$, the experimental results obtained from the moiré technique (named the roughness index) were utilized. The moiré is a similar effect of light and dark bands or fringes, produced by the superposition of two sets of grating lines when certain required circumstances are satisfied [23]. The mentioned 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). The properties of the moiré pattern such as the number of moiré lines, their thickness and area is affected by fabric surface properties. After the projection of grating lines and their superposition with the fabric, the resultant moiré patterns were captured by a digital camera. In the next stage an image processing procedure was carried out to measure the number and the area of moiré lines.

In order to normalize the calculated area, the measured area was divided by the number of moiré lines, so it was possible to have the area of moiré pattern per line and in this way the calculation errors diminished. It was proved that this factor can be used as an indicator for surface roughness of fabrics and it is called "roughness index", which is found to be a proper indicator and quantifier of fabric surface roughness. The values of roughness index for all sample groups are shown in Table 2. It should be mentioned that the surface roughness assessment of woven fabrics by moiré technique is thoroughly presented in another paper[24]. However, the experimental data obtained from the moiré technique was used to determine model coefficients (A0... A5). The normalized values of the mentioned parameters and also the roughness index value obtained from moiré technique are shown in Table 3.

In this regard, among 25 different samples, first 20 samples were used for training the model and finding the appropriate coefficients for the model and then 5 samples were used for testing the efficiency of the model. The correlation between the model and the experimental results will be discussed in the following sections.

In case the fabric is constructed from basic patterns as used in this study (Table 1), the yarns configuration is the same for all of the yarns in a repeat and they are only arranged in different positions in relation to other yarns of a repeat. However, if the fabric is assembled from a combination of various patterns (complex patterns), each

Table 2— Model parameters for various fabrics (raw data)

Fabric code	N	L_d, mm	K	L_y, mm	$\frac{Lu}{Ld}$	Roughness index, moiré
F1	220	0.4137	110	0.4545	1.1971	4382.0
F2	250	0.3403	125	0.4000	1.3509	3341.6
F3	280	0.2700	140	0.3571	1.6450	2869.3
F4	320	0.2275	160	0.3225	1.8348	2865.5
F5	340	0.1854	170	0.2941	2.1726	1844.3
F6	110	0.4147	55	0.4545	3.3844	3855.3
F7	125	0.3388	63	0.4000	3.7229	3141.1
F8	140	0.2778	70	0.3571	4.1422	2091.6
F9	155	0.2275	78	0.3225	4.6697	1659.7
F10	170	0.1854	85	0.2941	5.3451	1491.4
F11	73	1.3237	110	0.4545	1.0602	4964.9
F12	83	1.1388	125	0.4000	1.1075	3936.8
F13	93	0.9920	140	0.3571	1.1599	3531.2
F14	103	0.8725	155	0.3225	1.2177	3289.9
F15	113	0.7736	170	0.2941	1.2810	2006.0
F16	110	0.8692	110	0.4545	1.0917	4583.2
F17	125	0.7388	125	0.4000	1.1657	3442.6
F18	140	0.6349	140	0.3571	1.2499	3305.7
F19	155	0.5500	155	0.3225	1.3453	2937.8
F20	170	0.4795	170	0.2941	1.4534	1879.3
F21	147	0.4147	73	0.4545	2.2883	4123.6
F22	167	0.3388	83	0.4000	2.5422	3194.0
F23	187	0.2778	93	0.3571	2.8567	2387.4
F24	213	0.2275	107	0.3225	3.2523	2076.3
F25	227	0.1854	113	0.2941	3.7589	1809.9

Table 3— Model parameters for various fabrics after normalization

Fabric code	N	L_d mm	K	L_y mm	$\frac{Lu}{Ld}$ mm	Roughness index, moiré
F1	0.5500	0.2006	0.4783	1.0000	0.0320	0.8322
F2	0.6625	0.1361	0.6087	0.6602	0.0678	0.5327
F3	0.7750	0.0743	0.7391	0.3928	0.1365	0.3967
F4	0.9250	0.0370	0.9130	0.1771	0.1808	0.3956
F5	1.0000	0.0000	1.0000	0.0000	0.2596	0.1016
F6	0.1375	0.2014	0.0000	1.0000	0.5424	0.6806
F7	0.1938	0.1347	0.0652	0.6602	0.6214	0.4749
F8	0.2500	0.0812	0.1304	0.3928	0.7193	0.1728
F9	0.3063	0.0370	0.1957	0.1771	0.8424	0.0485
F10	0.3625	0.0000	0.2609	0.0000	1.0000	0.0000
F11	0.0000	1.0000	0.4783	1.0000	0.0000	1.0000
F12	0.0375	0.8376	0.6087	0.6602	0.0110	0.7040
F13	0.0750	0.7086	0.7391	0.3928	0.0233	0.5872
F14	0.1125	0.6037	0.8696	0.1771	0.0368	0.5178
F15	0.1500	0.5168	1.0000	0.0000	0.0515	0.1482
F16	0.1375	0.6007	0.4783	1.0000	0.0073	0.8901
F17	0.1938	0.4862	0.6087	0.6602	0.0246	0.5617
F18	0.2500	0.3949	0.7391	0.3928	0.0443	0.5223
F19	0.3063	0.3203	0.8696	0.1771	0.0665	0.4164
F20	0.3625	0.2584	1.0000	0.0000	0.0918	0.1117
F21	0.2750	0.2014	0.1594	1.0000	0.2866	0.7578
F22	0.3500	0.1347	0.2464	0.6602	0.3459	0.4902
F23	0.4250	0.0812	0.3333	0.3928	0.4193	0.2580
F24	0.5250	0.0370	0.4493	0.1771	0.5116	0.1684
F25	0.5750	0.0000	0.5072	0.0000	0.6298	0.0917

yarn in a repeat of the pattern should be independently analyzed and the superposition of the effect of different yarn configurations on roughness must be considered.

3 Results and Discussion

3.1 Model Coefficients Extraction in Association with Experimental Data

As mentioned earlier, from the 25 samples tested in this study, 20 samples were selected for training and subsequently for finding the coefficients of the model. In addition, the five remaining samples were used for testing the efficiency of the model. The five samples were chosen in a manner that they have the least similarity in their properties and have enough diversity. These five specimens were F5, F7, F11, F18 and F24, the properties of which are shown in Table 1.

In order to extract the model coefficients, the value of roughness index as calculated from the moiré fringe projection method is used. For diminishing the error and also better fitting of the model to data, the figures of the roughness index are also normalized by using Eq. (1), to set the data between 0 and 1 (Table 3).

By utilizing the linear backward regression method for 20 samples, the appropriate coefficients for the roughness model are attained and the model can be written as:

$$\mathrm{Rm} = -0.275 + 0.237 \times N + 0.45 \times L_d + 0.25 \times K + 0.748 \times L_Y + 0.107 \times \left(\frac{Lu}{Ld}\right) \quad \ldots (3)$$

The correlation between the data obtained from the experimental method (roughness index) and the roughness model (Rm) is clear in Fig. 2(a). As it is obvious in this figure, the proposed model can properly correlate the experimental data at the confidence range of 95% (R^2=0.9429).

In the next stage, the efficiency of the model has been tested through feeding the characteristics of 5 test specimens to the model and then the output of the model is analysed. As it is shown in Fig. 2(b), the high correlation between the model output and the experimental data is the evidence for the success of the model for the roughness assessment of woven fabrics.

3.2 Subjective Surface Roughness Evaluation Results

The data collected from the subjective tests were employed and the roughness scale value for various weave structures was calculated.

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

The results achieved from subjective tests (roughness scale value) are used to check the validation of the values of the Rm obtained from the model. In this regard, the correlation between the 'subjective roughness scale values' and 'Rm' for various patterns is investigated. The analysis of results reveals that there is an adequate correlation (R-squared value in the range of 0.9128 to 0.9939) between the results of both subjective tests and model. In other words, Rm which is achieved from the model is a suitable indicator of the surface roughness and can be effectively used for the evaluation and prediction of the surface roughness of woven fabrics. The correlations between 'Rm' and the 'roughness scale value' for various weave structures, in different weft densities are visible in Fig.3.

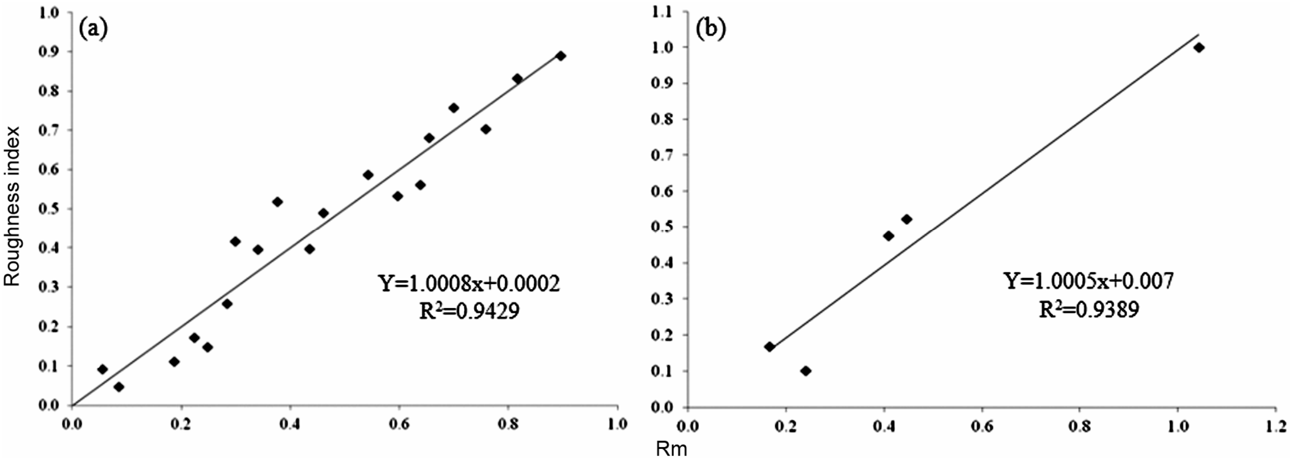

Fig.2— Correlation between model and experimental data (a) 20 training samples, and (b) 5 testing samples

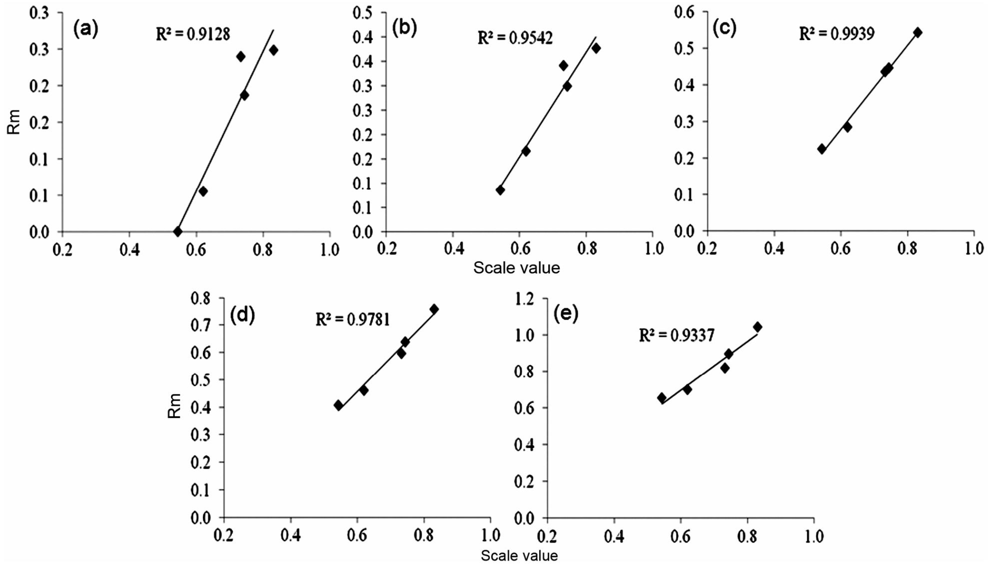

Fig.3—Correlation between model output and subjective scale value, [weft density (a) 34/cm, (b) 31/cm, (c) 28/cm, (d) 25/cm and (e) 22/cm]

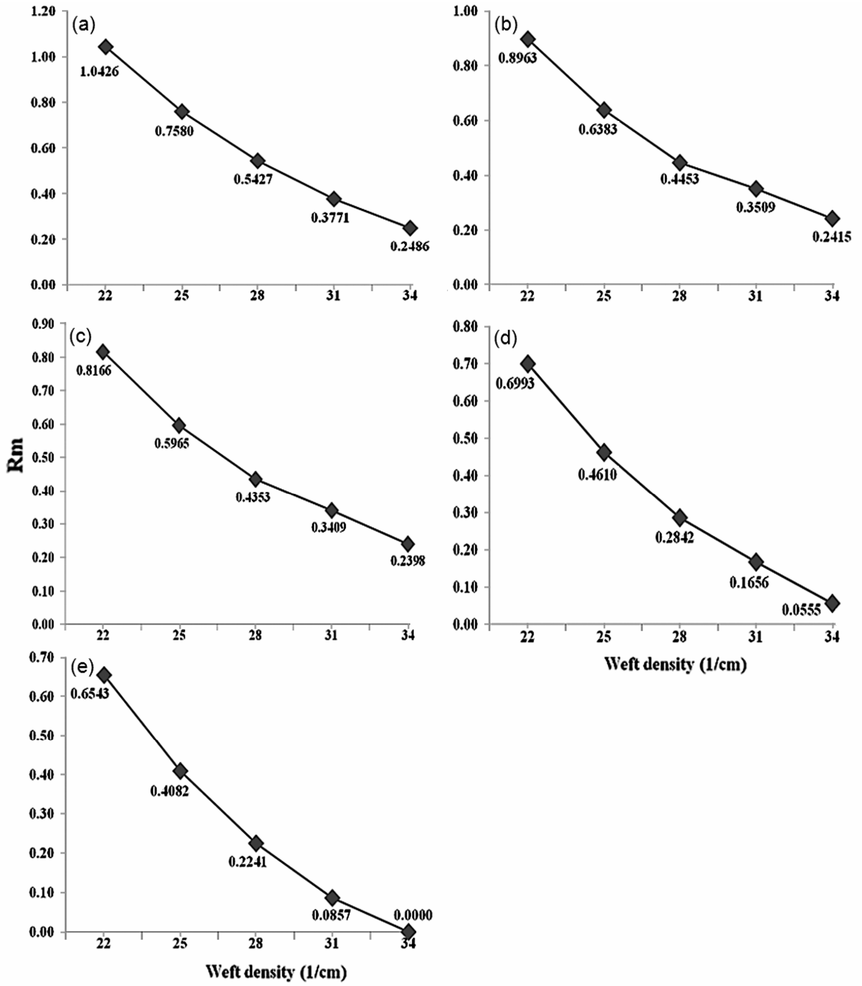

Fig. 4— Effect of weft density on fabric surface roughness, [weave structure (a) twill 3/3, (b) twill 2/2, (c) plain, (d) twill 2/1, and (e) twill 3/1]

3.3 Effect of Fabric Structural Parameters on Surface Roughness

The values of the roughness achieved from the model (Rm) in relation to the weft density of fabrics are investigated. The analysis of results reveals that by increasing the weft density of the fabric, the value of Rm decreases and the surface of the fabric becomes smoother. As it is shown in Fig. 4, this trend is shown in various weave structures.

By increasing the number of yarns in a same unit length of the fabric, the gaps between yarns in the fabric structure reduces and the constancy of the fabric rises, thus making the surface becomes smoother.

Moreover, the analysis of the roughness data was carried out in order to study the influence of fabric weave structure on the surface roughness of the tested fabrics. In this regard, the diagrams of the model output (Rm) for different weave structures are plotted. As it is clear in Fig.5, in all density groups, twill 3/3 has the highest value of Rm. The estimated roughness for twill 2/2 is found to be more than the plain, while twill 2/1 is smoother than the plain. Finally, the lowest value for roughness index is achieved for twill 3/1.

Thus, it can be concluded that twill 3/3 is the roughest and twill 3/1 is the smoothest fabric. This result is in accordance with the subjective tests.

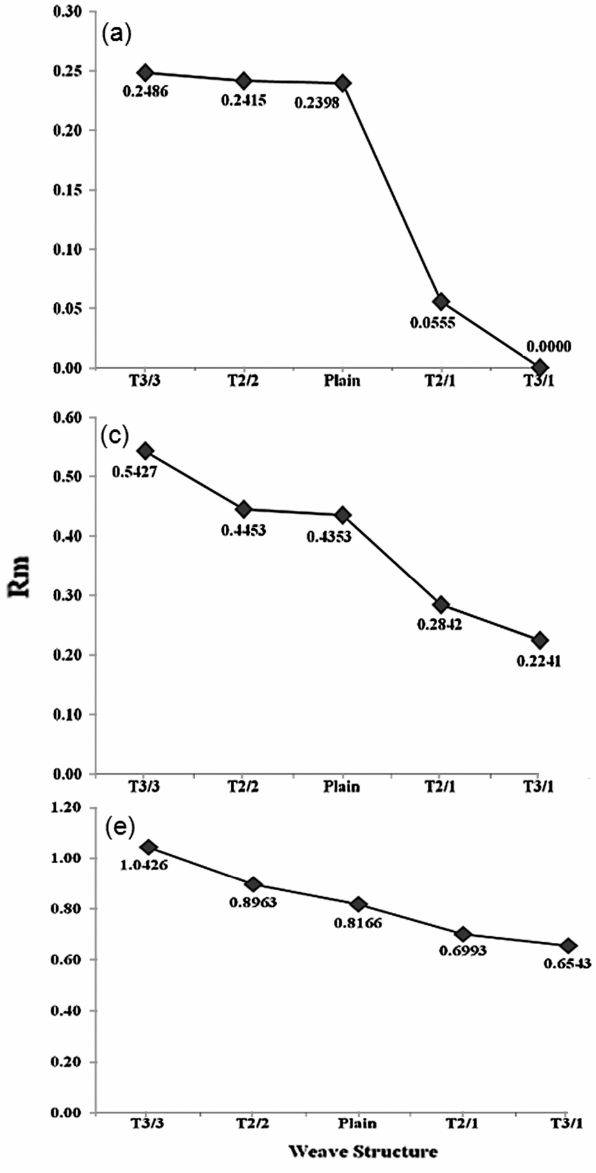

Fig. 5— Effect of weave structure on fabric surface roughness, [weft density (a) 34/cm, (b) 31/cm, (c) 28/cm, (d) 25/cm, and (e) 22/cm]

4 Conclusion

Fabric surface roughness, has been investigated by modelling the surface roughness, using woven fabrics' geometrical parameters. The geometrical roughness model was presented for the prediction of the surface roughness of woven fabrics with various structures. The fabric's geometrical parameters such as the number of warp and weft interlacing points, the non-floating length of the yarn on the fabric surface, the number of yarns positioned in the non-floating region, the distance between yarns in the non-floating region and the fraction of the floating and non-floating length of the yarn on the fabric surface are fed to the model and the surface roughness of the woven fabric is estimated. The output of the model was validated via a set of subjective pair-comparison tests with an acceptable correlation (R-squared value of more than 0.9128).

The investigation of the roughness results reveals that the effect of fabric structural parameters such as weave structure and weft density is significant on the roughness at the confidence range of 95%. By increasing the weft density of fabrics, the surface roughness of fabrics decreases. It is also observed that twill 3/3 is the roughest weave structure while twill 3/1 is the smoothest one. These results are found to be in accordance with the subjective tests.

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