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Characterisation and Application of Objective Pilling Classification to Patterned Fabrics

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Previously, the authors proposed a new, simple method of frequency domain analysis based on the two-dimensional discrete wavelet transform to objectively measure the pilling intensity in sample fabric images. The method was further characterised and the results obtained indicate that standard deviation and variance are the most appropriate measure of the dispersion of wavelet details coefficients for analysis, that the relationship between wavelet analysis scale and fabric inter-yarn pitch was empirically confirmed, and, that fabrics with random patterns do not appear to impact on the effectiveness of the analysis method.

Keywords: Objective pilling rating; Wavelet transform; Patterned fabrics; Image analysis

1. INTRODUCTION

Fabric pilling is a serious problem for the apparel industry (Ukponmwan et al., 1998). Pills cause an unsightly appearance and can cause premature wear (Ramgulam et al., 1993). A key element in the control of fabric pilling is the evaluation of resistance to pilling by testing. Resistance to pilling is normally tested in the laboratory by processes that simulate accelerated wear, followed by a manual assessment of the degree of pilling by an expert based on a visual comparison of the sample to a set of test images (Abril et al., 1998). A frequent complaint about the manual/visual evaluation method is the inconsistency and inaccuracy of the rating results (Latifi et al., 2001; Xu, 1997). In an attempt to bring more objectivity into the pilling rating process, a number of automated systems based on image analysis have been developed and described in the literature (Abril et al., 1998; Amirbayat and Alagha, 1994; Hsi et al., 1998a; Hsi et al., 1998b; Konda et al., 1988; Panhuber et al., 1994; Sirikasemleert and Tao, 2000; Xin et al., 2002; Xu, 1997). All of these existing methods either employ expensive and complicated equipment, such as laser triangulation imaging (Ramgulam et al., 1993; Sirikasemleert and Tao, 2000), and/or employ complex image processing algorithms that involve multiple stages (Abril et al., 1998; Xin et al., 2002; Xu, 1997). More recently, approaches suitable for the objective assessment of pilling of patterned fabrics using image analysis have been documented (Chen and Huang, 2004; Kang et al., 2004), but, these methods also employ complex hardware and software systems to complete the task. At least one system for objective pilling analysis (including patterned fabrics) is commercially available (Dakin, 2005), but, no independent assessment of its performance is currently available.

In earlier works (Palmer and Wang, 2003; Palmer and Wang, 2004) we described a simple methodology for the objective classification of fabric pilling based on the two dimensional discrete wavelet transform (2DDWT). When a fabric image is analyzed using the 2DDWT, at each wavelet analysis scale, there will be a distribution of detail coefficients (distribution of cD_n^o; where n is the analysis scale and o is the orientation – horizontal, vertical or diagonal). We proposed that for 2DDWT analysis of un-pilled fabric images, where the wavelet scale is close to the fabric inter-yarn pitch, the distribution of cD_n^o will have a relatively small standard deviation ($SDcD_n^o$), and, as the amount of pilling increases, $SDcD_n^o$ will increase as the pills introduce variations into the image that disrupt the underlying pattern of the fabric structure. It was further proposed that it would be possible to apply this image analysis method to a set of reference fabric pilling samples to develop a calibrated characteristic curve that relates pilling intensity to $SDcD_n^o$.

The results obtained previously suggested that the method was feasible, and that the ability of the method to discriminate between levels of pilling intensity was dependent on the wavelet analysis scale being closely matched to the fabric inter-yarn pitch. We presented a heuristic method for the optimal selection of an analysis wavelet and associated analysis scale. The results obtained suggested that the Haar wavelet was a reasonable basis for analysis; we suggested that this was due to its square wave structure approximating the weave/knit fabric structure. We also found that the method was robust to small horizontal and/or vertical translations of the image under analysis, was robust to significant variations in the brightness of the image under analysis, was sensitive to rotation of the image under analysis, and was sensitive to dilation of the image under analysis.

Here, we further evaluate the method to investigate alternative measures of dispersion of cD_n^o (other than standard deviation), to confirm the relationship between wavelet analysis scale and fabric inter-yarn pitch, and, to investigate the application of this alternative, simple analysis method to patterned fabrics.

2. INVESTIGATION OF MEASURES OF DISPERSION

The previously described wavelet analysis method was based on using the standard deviation as a measure of dispersion of the distribution of the wavelet detail coefficients. However, there is a range of descriptive statistics that provide a measure of dispersion, including range, inter-quartile range, variance, standard deviation, mean absolute deviation, median absolute deviation, standard error and coefficient of variation (Black, 2004; Johnson and Kuby, 2000). A trial was conducted to identify the most appropriate measure of dispersion to use in the wavelet analysis method. The standard pilling test series used was the 1840 double jersey series from James H. Heal & Company Limited. The test images were scanned at 600 dots per inch (dpi), aligned (where necessary), cropped, and scaled to 512 by 512 pixels (to speed the wavelet analysis calculations). Figure 1 shows the images from this standard pilling test series for the supplier rated pilling intensities of 1 (maximum pilling), 3 and 5 (no pilling).

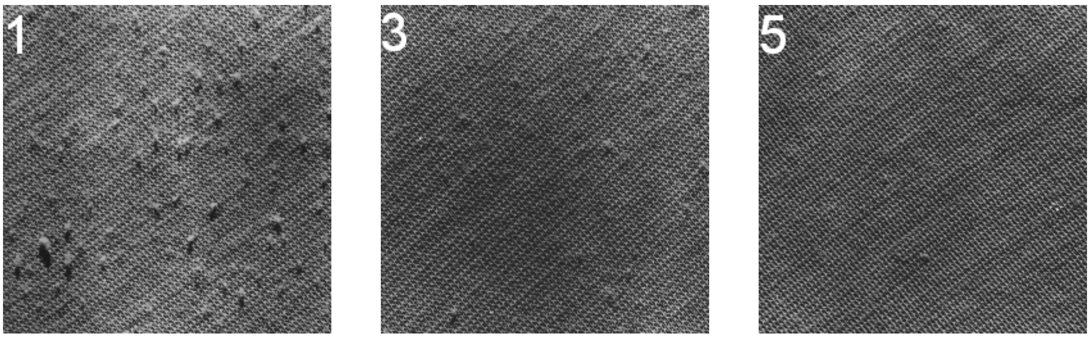

Figure 1. Standard pilling test images - 1840 double jersey series

A feasible basis for objective classification of pilling intensity is obtained when, for a particular analysis scale, a monotonic increase in the dispersion/spread of cD_n^o is observed for increasing pilling intensity. Where wavelet analysis produces multiple bases for objective classification of pilling intensity, we previously proposed a method for selecting the best basis (Palmer and Wang, 2003). For a given set of reference pilling test images, at a given analysis scale, we proposed a discrimination factor that is given by:

$$\frac{Step_{min}}{Step_{max}} \times Range \qquad (1)$$

where $Step_{min}$ is the minimum range of $SDcD_n^o$ between adjacent levels of pilling, $Step_{max}$ is the maximum range of $SDcD_n^o$ between adjacent levels of pilling, and *Range* is the total range of $SDcD_n^o$ for the set of test images; where $SDcD_n^o$ for each test image increases monotonically with increasing intensity of pilling. The classification basis with the highest discrimination factor is the preferred basis.

The wavelet analysis was performed using the Matlab software package (The MathWorks Inc., 2004a) and Matlab Wavelet Toolbox (The MathWorks Inc., 2004b). Using the Haar wavelet, the horizontal detail coefficients (cD_n^h) for each of the five levels of pilling intensity were computed for eight levels (scales) of wavelet multiresolution analysis. For each of the 40 distributions of cD_n^h, the range, inter-quartile range, variance, standard deviation, mean absolute deviation, median absolute deviation, standard error and coefficient of variation were computed. At each analysis scale, for each of the six measures of dispersion of cD_n^h, observation was undertaken to identify any instances of monotonically increasing dispersion with increase in pilling intensity. Where such occurrences were found, the discrimination factor according to Equation 1 was computed. Tables I to III show the results obtained for standard deviation (SD), inter-quartile range (IQR), mean absolute deviation (MnAD), variance (Var), median absolute deviation (MdAD) and standard error (StdErr).

Table I

Measures of dispersion of cD_n^h versus pilling intensity, and resultant discrimination factor for Haar wavelet analysis of 1840 pilling image series

Dispersion / Scale	SD / 3	SD / 4	SD / 5	MnAD / 3	MnAD / 4
Pilling intensity 5	71.43	51.99	71.73	58.28	41.28
Pilling intensity 4	74.30	55.99	75.06	61.21	43.34
Pilling intensity 3	79.49	64.64	83.07	63.81	50.22
Pilling intensity 2	81.55	83.03	100.40	65.56	63.10
Pilling intensity 1	91.63	96.24	152.50	73.25	73.20
Discrimination factor	4.13	9.62	5.16	3.42	5.11

Table II

Measures of dispersion of cD_n^h versus pilling intensity, and resultant discrimination factor for Haar wavelet analysis of 1840 pilling image series

Dispersion / Scale	Var / 3	Var / 4	Var / 5	MdAD / 3	MdAD / 4
Pilling intensity 5	5102.6	2703.1	5145.0	50.94	35.28
Pilling intensity 4	5520.8	3135.1	5634.2	54.69	35.38
Pilling intensity 3	6319.0	4178.3	6900.7	54.88	39.63

Pilling intensity 2	6631.9	6894.7	10088.0	55.75	50.88
Pilling intensity 1	8396.4	9262.0	23242.0	62.19	55.91
Discrimination factor	584.09	1043.09	673.03	0.325	0.172

Table III

Measures of dispersion of cD_n^h versus pilling intensity, and resultant discrimination factor for Haar wavelet analysis of 1840 pilling image series

Dispersion / Scale	StdErr / 3	StdErr / 4	StdErr / 5	IQR / 3
Pilling intensity 5	1.12	1.62	4.48	101.94
Pilling intensity 4	1.16	1.75	4.69	109.75
Pilling intensity 3	1.24	2.02	5.19	111
Pilling intensity 2	1.27	2.59	6.28	112.25
Pilling intensity 1	1.43	3.01	9.53	124.5
Discrimination factor	0.060	0.301	0.323	2.30

It was noted that using the range and the coefficient of variation as a measure of dispersion of cD_n^h did not produce any feasible bases. The range is simple to calculate, but is based on only a small sample of the distribution (the two extreme values), and is strongly influenced by outlier values, making it of limited value as a descriptive measure of dispersion (Martin and Pierce, 2002). The coefficient of variation is the ratio of the standard deviation to mean (Black, 2004). However, in this application, the distribution of cD_n^o is roughly symmetrical about a mean value that is close to zero and may be of either sign. Hence, it is unlikely that the coefficient of variation will produce the required monotonic sequence of dispersion of

cD_n^o required. It was noted that the mean absolute deviation, median absolute deviation, standard error and inter-quartile range all produced feasible bases for analysis, though the discrimination factors obtained where all significantly less than the best result obtained for analysis bases derived from the standard deviation. It was noted that the variance also produced feasible bases for analysis, and that it also gave the largest discrimination factors by far, exceeding even the standard deviation.

The standard deviation is the positive square root of the variance (Rasmussen, 1992), so, where the standard deviation produces a feasible basis for analysis, the variance will also. As the standard deviation and variance share a direct but non-linear relationship, it is unclear whether the larger discrimination factor produced by the variation offers a significant improvement in the ability of analysis based on the variation to discriminate between successive levels of pilling intensity. On the face of it, the variation offers the largest discrimination factor, and is computationally simpler than the standard deviation. However, computation of the standard deviation is a widely supported standard mathematical function in many programming environments, and the standard deviation has the same linear units as the original data values, instead of the squared units of the variance. We conclude that either the standard deviation or variation provide an appropriate measure of dispersion to use in the wavelet analysis method. The standard deviation measure of dispersion will be used in the work that follows.

3. ANALYSIS METHOD RELATIONSHIP TO INTER-YARN PITCH

We previously proposed that the wavelet analysis method would yield the best results when the ‘resolution’ of the analysis (width of the analysis wavelet) at a particular multiresolution scale was close to the fabric inter-yarn pitch in pixels, for a given fabric image. A trial was conducted to verify this proposition. The standard pilling test series used was the 1840 double jersey series from James H. Heal & Company Limited. The test images were scanned at 600 dpi, aligned (where necessary) and cropped to 2048 by 2048 pixels. This original image was designated as ‘100%’ size. Using the Matlab software package (The MathWorks Inc., 2004a), scaled images were produced such that for each of the five original pilling standard images a series of 20 images were produced from 100 percent to 5 percent of the original image size, in 5 percent increments. Using the Matlab Wavelet Toolbox (The MathWorks Inc., 2004b), at each of the 20 image size points (five to 100 percent), using the Haar wavelet, the standard deviation of the horizontal detail coefficients ($SDcD_n^h$) for each of the five levels of pilling intensity were computed for nine levels (scales) of wavelet multiresolution analysis. At each analysis scale, observation was undertaken to identify any instances of monotonically increasing $SDcD_n^h$ with increase in pilling intensity. Where such occurrences were found, the discrimination factor according to Equation 1 was computed. Figure 2 shows the discrimination factors obtained for all analysis scales that produced a feasible analysis basis for all image size points.

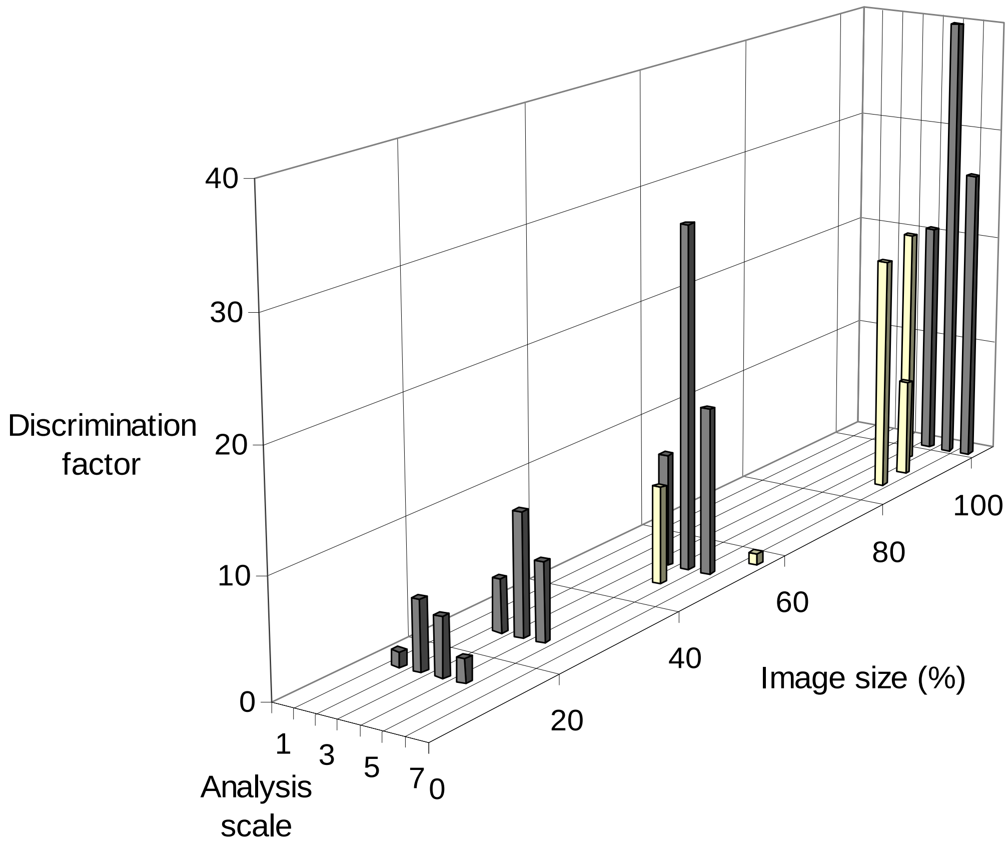

Figure 2. Discrimination factors obtained for all analysis scales that produced a feasible analysis basis for all image sizes - 1840 double jersey series

Previously we proposed that the 'resolution' of the analysis (related to the original image dimensions) at 'analysis scale *n*' is 2^{n-1} pixels, and, that the best discrimination factor would be obtained when the visible inter-yarn pitch in the image approximated the analysis scale resolution in pixels. Previously, it was observed that adjacent analysis scales may also produce feasible analysis bases, but with a lower discrimination factor than the scale that best matches the inter-yarn pitch. It was observed that the original '100%' images produced feasible analysis bases at scales five, six and seven, with the maximum discrimination factor at scale six. Feasible basis for analysis were observed at single scales for image sizes of 95, 90 and 85 percent. It was observed that the 50 percent images produced feasible analysis bases at scales four, five and six, with the maximum discrimination factor at scale five. Feasible basis for analysis were observed at single scales for image sizes of 55 and 45 percent. It was observed that the 25 percent images produced feasible analysis bases at scales three four and five, with the maximum discrimination factor at scale four.

The sizing of the original '100%' image was devised such that the image inter-yarn pitch was approximately 32 pixels, hence we would expect the best analysis basis for the 100 percent image to occur at scale six, as observed. Other feasible analysis bases were observed adjacent to the maximum discrimination factor, both as adjacent scales in the 100 percent image size, and as single feasible basis in image sizes close to the 100 percent image size. When the linear dimensions of the original image were reduced by half, the 50 percent image size was obtained. Here, the visible inter-yarn pitch was reduced to approximately 16 pixels, hence we would expect the best analysis basis for the 50 percent image to occur at scale five, as observed. Again, other feasible bases were observed around to the maximum discrimination factor in the 50 percent image size. When the linear dimensions of the original image were reduced to one quarter, the 25 percent image size was obtained. Here, the visible inter-yarn pitch was reduced to approximately 8 pixels, hence we would expect the best analysis basis for the 25 percent image to occur at scale four, as observed. Here, other feasible analysis bases were observed at adjacent scales for the 25 percent image size, but not at nearby image sizes.

These observations support the proposition that the best discrimination factor will be obtained when the visible inter-yarn pitch in the image approximates the analysis scale resolution in pixels. This can be observed in the way that the best analysis basis is found at the next lower analysis scale each time the size of the image (and hence the inter-yarn pitch) is halved. Additional feasible analysis bases are observed clustered around the expected best basis points, but these yielded a lower analysis discrimination factor, as might be expected where the analysis wavelet resolution matches less well with the fabric inter-yarn pitch. To further investigate the relationship between the analysis method and the inter-yarn pitch, the '100%' image was used to produce a '12.5%' image (i.e., half the size of the 25 percent image size). When analyzed, again, the best analysis basis was observed at a scale one lower than for the 25 percent image size, and other feasible, but non-optimal, analysis bases were observed at adjacent analysis scales. In figure 2, the data for the '12.5%' image has been included, and the data for 'the power of two' images sizes where the maximum discrimination factors are located are shaded darkly, and the remaining isolated feasible analysis bases are shaded lightly.

This work highlights the presence of feasible analysis bases at multiple scales within the image. While the analysis method described here seeks a single optimum wavelet scale basis on which to simply discriminate between pilling intensities, the presence of feasible analysis bases at multiple scales suggests the possibility of more sophisticated analysis that might combine wavelet data from multiple scales, such as wavelet texture analysis (Bharati and MacGregor, 2004).

4. APPLICATION OF THE ANALYSIS METHOD TO PATTERNED FABRICS

Many real fabrics are patterned, so a trial was conducted to investigate the performance of the analysis method on patterned textiles. As none of the available standard pilling intensity test image sets employed patterned fabrics, two of these test image sets for which a feasible analysis basis had previously been found were selected, and simulated patterns were superimposed on them. The standard pilling intensity test image sets chosen were the IWS SM54 Botany knitted series, and the 1842 woven series from James H. Heal & Company Limited; these two sets cover the principal regular fabric construction types. The test images were scanned at 600 dpi, aligned (where necessary), cropped, and scaled to 512 by 512 pixels. For each of the five pilling intensities from both test image sets, a series of three patterned images were created using the Adobe PhotoDeluxe program (Adobe Systems Incorporated, 1997) by:

1. leaving two repeats of the principal horizontal weave dimension unchanged, increasing the brightness of the next two weave repeats by 100 percent (i.e., double the mean pixel value), then repeating (regular pattern image);
2. leaving two repeats of the principal horizontal weave dimension unchanged, increasing the brightness of the next two weave repeats by 100 percent, leaving 12 weave repeats unchanged, increasing the brightness of the next two weave repeats by 100 percent, then repeating (irregular pattern image); and
3. applying a random pattern of five scalene triangles to the original image and increasing the brightness within the triangle areas by 100 percent (random pattern image).

Figure 3 shows the original pilling intensity five (unpilled) test image for the 1842 woven series from James H. Heal & Company Limited, plus the three simulated patterned test images created.

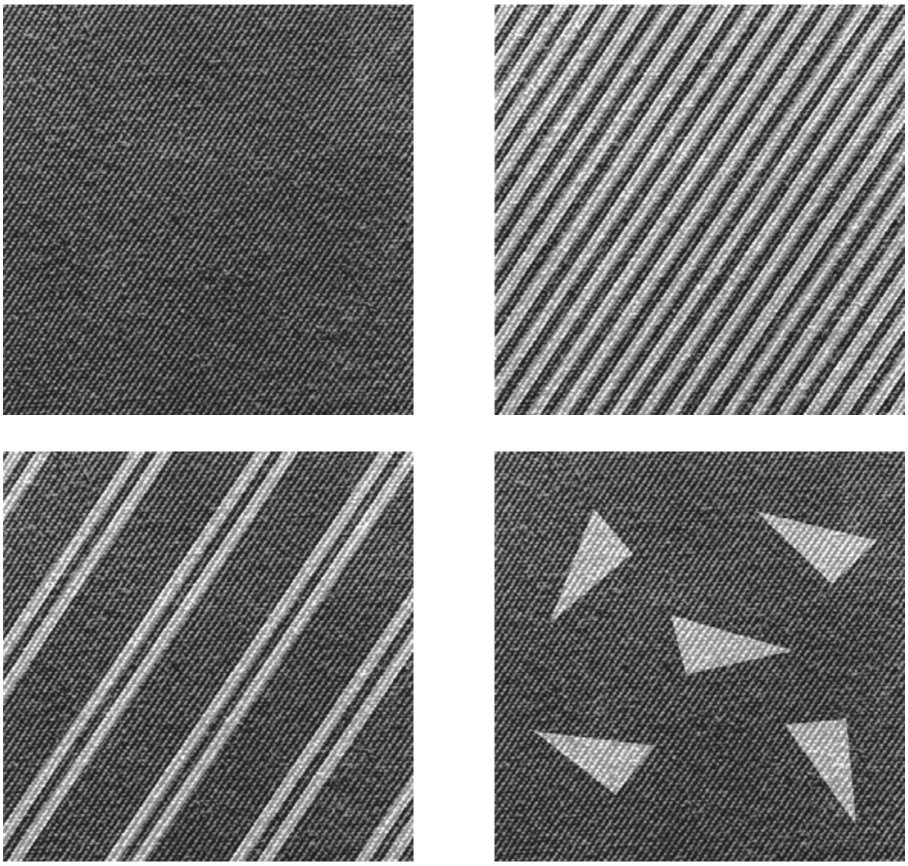

Figure 3. Original image, plus simulated regular, irregular and random patterned test images – for James Heal 1842 woven series, pilling intensity 5 image

Using the Matlab Wavelet Toolbox (The MathWorks Inc., 2004b), for each of the original and three patterned images sets, for each of the fabric constructions (knitted and woven), and using the Haar wavelet, the standard deviation of the horizontal detail coefficients ($SDcD_n^h$) for each of the five levels of pilling intensity were computed for eight levels (scales) of wavelet multiresolution analysis. At each analysis scale, observation was undertaken to identify any instances of monotonically increasing $SDcD_n^h$ with increase in pilling intensity. Where such occurrences were found, the discrimination factor according to Equation 1 was computed. Tables IV to VI show the results obtained.

Table IV

$SDcD_n^h$ versus pilling intensity, and resultant discrimination factor for Haar wavelet analysis of knitted patterned IWS SM54 Botany pilling image series

Construction Pattern / Scale	Knitted Original/4	Knitted Original/5	Knitted Regular/3	Knitted Regular/4	Knitted Regular/5
Pilling intensity 5	100.29	124.43	72.19	81.57	98.87
Pilling intensity 4	105.59	154.59	75.85	98.71	143.53
Pilling intensity 3	116.67	154.78	79.15	109.58	145.54
Pilling intensity 2	138.11	175.71	80.74	125.30	159.94
Pilling intensity 1	146.66	190.19	89.49	136.90	176.16
Discrimination factor	11.46	0.41	3.15	35.08	3.48

Table V

$SDcD_n^h$ versus pilling intensity, and resultant discrimination factor for Haar wavelet analysis of knitted patterned IWS SM54 Botany pilling image series

Construction Pattern / Scale	Knitted Irregular/4	Knitted Irregular/5	Knitted Random/4	Knitted Random/5
Pilling intensity 5	91.90	112.10	133.04	281.48
Pilling intensity 4	101.50	148.45	142.55	315.36

Pilling intensity 3	113.09	148.83	151.64	320.87
Pilling intensity 2	132.64	169.25	170.27	327.97
Pilling intensity 1	141.57	182.81	177.81	333.54
Discrimination factor	22.69	0.74	18.12	8.47

Table VI

$SDcD_n^h$ versus pilling intensity, and resultant discrimination factor for Haar wavelet analysis of woven patterned 1842 pilling image series

Construction Pattern / Scale	Woven Original/4	Woven Original/5	Woven Random/4	Woven Random/5
Pilling intensity 5	65.00	61.78	119.08	300.44
Pilling intensity 4	69.08	78.56	120.67	301.98
Pilling intensity 3	115.65	167.55	153.99	331.76
Pilling intensity 2	123.98	188.61	160.41	348.91
Pilling intensity 1	126.11	200.77	160.64	370.49
Discrimination factor	2.79	18.99	0.29	3.62

The original knitted images produced feasible analysis bases at scales four and five, with the best basis at scale four. The regular patterned version of the knitted images produced feasible analysis bases at scales three, four and five, with the best basis at scale four. Interestingly, the best discrimination factor for the regular patterned image exceeded that of the original images. This may be because the knitted fabric, while having a repeating construction structure, is formed from circular loops, and does not have a frequency domain ‘signature’ that is as distinct as a regular linear weave. The introduction of the regular pattern superimposed on the original knitted image data appears to have introduced a more distinct underlying frequency structure, which is the basis for the wavelet analysis method. The irregular patterned version of the knitted images produced feasible analysis bases at scales four and five, with the best basis at scale four. As for the regular patterned images, the best discrimination factor exceeded that of the original images, though, to a lesser extent, possibly because the frequency domain signature of the irregular pattern is less distinct than the regular pattern. The random patterned version of the knitted images produced feasible analysis bases at scales four and five, with the best basis at scale four. The best discrimination factor was larger than that of the original images, however, the total range of $SDcD_4^h$ was virtually identical, suggesting that the imposition of the random pattern (which should not alter the frequency domain signature of the images in any systematic way) had little impact on the analysis method.

The original woven images produced feasible analysis bases at scales four and five, with the best basis at scale five. Both the regular and irregular patterned versions of the woven images did not produce any feasible analysis bases. This was probably due to the fact that the original woven images had a very sharp frequency domain signature centred around the horizontal repeat rate of the fabric inter-yarn pitch, and, the introduction of the additional regular horizontal frequency components close to the original fabric weave frequency disrupted the ability of the wavelet analysis to discriminate between the underlying fabric structure and pilling ‘noise’. The random patterned version of the woven images produced feasible analysis bases at scales four and five, with the best basis at scale five.

These results suggest the possibility of superimposing an artificial underlying frequency structure, using image brightness modification, to improve the discrimination factor obtained for fabric types whose original frequency structure might otherwise be difficult to analyze. Additionally, that woven fabrics with regular patterns close to the inter-yarn pitch of the fabric weave, may not be good candidates for wavelet analysis. And, that the introduction of random patterns, while impacting on the absolute values of discrimination factor obtained, does not appear to impact on the existence and scale location of feasible analysis bases.

5. CONCLUSIONS

A previously proposed method of frequency domain analysis based on the two-dimensional discrete wavelet transform to objectively rate the pilling intensity in sample images was further evaluated. The method is based on the computation of the dispersion of the distribution of wavelet detail coefficients for the images under analysis. A range of measures of dispersion were trialled, and the best results were obtained using the standard deviation and variance. As these two measures of dispersion are directly related, it is concluded that either measure can be adopted for the analysis method. It was previously proposed that the best basis for analysis would occur when the wavelet analysis scale closely matched the fabric inter-yarn pitch. A series of pilling test images were generated with varying apparent inter-yarn pitches and were analyzed. It was found that feasible bases for analysis clustered around the intersection of analysis scales and the corresponding image size with an inter-yarn pitch matching that analysis scale, with the maximum analysis discrimination factors occurring at the intersections. The application of the method to the analysis of patterned fabrics was tested. It was found that fabrics with a regular weave structure and a regular pattern close to the inter-yarn pitch may not be good candidates for the analysis method, but, that random patterns do not appear to impact on the existence and scale of location of feasible analysis bases.

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