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Objective Classification of Fabric Pilling Based on the Two-Dimensional Discrete Wavelet Transform

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ABSTRACT

A number of methods for the automated objective rating of fabric pilling based on image analysis are described in the literature. The periodic structure of fabrics makes them suitable candidates for frequency domain analysis. The authors propose a new method of frequency domain analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively measure the pilling intensity in sample images. A preliminary evaluation of the proposed method based on analysis of two series of standard pilling evaluation test images is presented. The initial results obtained suggest that the proposed method is feasible, and that the ability of the method to discriminate between levels of pilling intensity is dependent on the wavelet analysis scale being closely matched to the fabric inter-yarn pitch. A heuristic method is also presented for the optimal selection of an analysis wavelet and associated analysis scale.
Fabric pilling is a serious problem for the apparel industry. Pills cause an unsightly appearance and can cause premature wear [18]. 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 [3]. A frequent complaint about the manual/visual evaluation method is the inconsistency and inaccuracy of the rating results [26]. 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 [3, 4, 9, 20, 26]. All of these existing methods either employ expensive and complicated equipment, such as laser triangulation imaging [18, 20], and/or employ complex image processing algorithms that involve multiple stages [3, 26].

A number of sources in the literature note the use of frequency domain image processing [3, 5, 25]. These sources describe variations in the use of the two-dimensional discrete Fourier transform (2DDFT) to separate periodic structures in the image (the fabric weave/knit pattern) from non-periodic structures in the image (the pills). The 2DDFT can only provide gross summary spatial frequency information about the entire image, it cannot provide location information. Fabric defects such as pills are localized in nature and cannot easily be identified directly by the Fourier transform [6]. For this reason, many of the existing techniques described in the literature employ a complex mixture of spatial domain and frequency domain processing stages to characterize image elements in both location and frequency.

The authors propose a new method of frequency domain analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively measure the pilling intensity in sample images. This paper presents an explanation of the proposed
method, a preliminary evaluation of the proposed method based on analysis of two series of standard pilling evaluation test images and a heuristic method for selecting an optimal analysis wavelet and complementary analysis scale for a given pilling classification case.

**Frequency Domain Analysis of Textiles**

It is possible to detect localized features in a one-dimensional signal using the short-time Fourier transform, and a two-dimensional analogue of this method, termed the space-dependent Fourier transform, has been used to identify localized fabric defects [5]. Another tool for frequency domain analysis is the wavelet transform, and this technique has the advantage of providing information about the data that is localized in both frequency and location. The literature includes examples of the application of the wavelet transform in the identification of fabric faults [11, 13, 14, 19, 24]. Detailed mathematical treatments of the wavelet transform are available elsewhere [15] but, in principle, the one-dimensional continuous wavelet transform (1DCWT) involves the comparison of a small waveform (wavelet – a time-limited waveform with special mathematical properties) with a section of the data under test. The process produces a coefficient that represents the ‘match’ between the data and the wavelet. The wavelet is translated by a small distance, and the comparison is repeated, in this way, the 1DCWT provides characteristic information about the data that is localized in position. Then, the wavelet is dilated (scaled up) and the process is repeated over a range of scales. Each different scale produces characteristic information about the image localized in frequency (or, more properly, localized in scale, but scale can be related to frequency).
Rather than calculating the 1DCWT at every possible scale and position, if we choose scales and positions based on powers of two, (and satisfy some additional mathematical criteria) we have the orthogonal form of the discrete wavelet transform (DWT). There exist efficient algorithms for computing the DWT that yield a fast wavelet transform analogous to the fast Fourier transform. At each analysis scale the DWT yields ‘approximation’ coefficients that represent low frequency (high scale) components of the data/signal, as well as ‘detail’ coefficients that represent high frequency components of the signal. The approximation forms the input to the analysis for the next successive scale decomposition, and the detail is a measure of the match between the signal and the wavelet at the current analysis scale. The multi-scale decomposition of the source data by iterative DWT analysis is known as ‘multiresolution analysis’. The DWT can be extended into two dimensions for image analysis in a way analogous to the 2DDFT. Here the analysis at each scale yields an approximation of the original image and three sets of details that represent the horizontal, vertical and diagonal details in the original image. This is the 2DDWT.

The approximation coefficients can be used to reconstruct the image based on the wavelet at the current analysis scale, and the details provide a measure of the ‘fit’ of the wavelet with the image data in the particular orientation (horizontal, vertical or diagonal) at the current analysis scale. At each 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); if the distribution is narrow, then the wavelet matches well with the image data in the current direction at the current scale; if the distribution is wide, then the wavelet matches less well with the image data. The authors propose 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 is further proposed that it is 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 \( SDcD_n^o \) obtained by analysis of a fabric test sample. In this way it is possible to perform an evaluation of pilling intensity that is analogous to the visual comparison method but, once calibrated for a given fabric type and test environment, will yield an objective measure without human interpretation. Compared to previous image analysis techniques described in the literature, the proposed method has the advantage that it requires only a single-stage of analysis to produce a quantitative measure of pilling intensity.

**Basic Analysis Method**

To evaluate the proposed method of pilling analysis two series of standard pilling evaluation test images were subjected to 2DDWT analysis and the standard deviation of the horizontal detail coefficients \( (SDcD_n^h) \) at the first five scales of analysis were recorded. The standard pilling test series used were the 1840 double jersey series and 1842 woven series from James H. Heal & Company Limited. The test images were scanned at 600 dots per inch, rotated (where necessary) to have approximately the same orientation of fabric structure, cropped of edge markings to 2048 by 2048 pixels, and then scaled to 512 by 512 pixels to speed the wavelet analysis calculations. Figure 1 and Figure 2 show these standard pilling test series with the supplier rated intensity of pilling indicated on a scale of 1 to 5.
Figure 1. Standard pilling test images - 1840 double jersey series.
Figure 2. Standard pilling test images - 1842 woven series.
The 2DDWT method employs a comparison wavelet as basis for analysis. There exist a large number of possible wavelets with varying mathematical properties that make them suited to particular analysis applications [12]. There are no clear rules for selecting the ‘best’ wavelet for a particular analysis application [12] [17], though intuitively one would expect that an analysis wavelet similar in form to the signal being analyzed would yield a better result than one with no similarity to the signal being analyzed. Shape similarity between the wavelet function and the features in the data to be analyzed is one of the selection criteria noted in the literature [8]. The simplest wavelet is the Haar wavelet [1], which has the general appearance of a square wave – see Figure 6(a), and it is suggested as an analysis basis for data with ‘jump’ or ‘step’ features [23], as would be expected to be found in the image data from the repeating pattern of a fabric. Analysis using the Haar wavelet is also computationally simpler than many other wavelets [17]. On these bases, the Haar wavelet was chosen for the initial analysis trials presented below. Following initial confirmation of the utility of the proposed method, the performance of the Haar wavelet as an analysis basis will be compared to other possible wavelet bases, and a heuristic method for the selection of an analysis wavelet and complementary analysis scale for a given set of reference pilling test images will be developed.

The wavelet analysis was performed using the Matlab Wavelet Toolbox [22], which provides a graphical user interface environment in which analysis can be performed easily up to five scales of decomposition. Initial trials examined the horizontal detail coefficients (\(cD^n\)), as the image properties in the horizontal direction are representative of the entire image. For both the 1840 double jersey series and the 1842 woven series the horizontal fabric structure pattern was found to repeat approximately every 8 pixels. Figure 3 and Figure 4 present \(SDcD^n_h\) from the
2DDWT analysis of the two standard test image series for the first five analysis scales of decomposition.

Figure 3. $SDcD_n^h$ versus standard test image pill intensity rating for 2DDWT analysis levels 1 to 5 (i to v) - 1840 double jersey series.
Figure 4. $SDcD^h_n$ versus standard test image pill intensity rating for 2DDWT analysis levels 1 to 5 (i to v) - 1842 woven series.

For the case of the 1840 double jersey series, it can be seen that the scale 3, scale 4 and scale 5 analyses produced a monotonic, but non-linear increase in $SDcD^h_n$ with increasing pilling intensity, with the widest range coming from the scale 5 wavelet analysis. For the case of the 1842 woven series, it can be seen that the scale 4 and scale 5 analyses produced a monotonic, but non-linear increase in $SDcD^h_n$ with increasing pilling intensity, with the widest range coming from the scale 5 wavelet analysis.
At each scale of wavelet analysis, the new approximation of the original image is developed by performing the analysis on the current approximation of the image and then decimating the computed wavelet coefficients in both dimensions by half, reducing the linear dimensions of the image by half and the image area by three quarters for each analysis level. Hence, the ‘resolution’ of the analysis (related to the original image dimensions) at ‘analysis scale n’ is $2^{-n}$ pixels. At low analysis scales the analysis resolution is small (at scale 1 the resolution is 1 pixel; at scale 3 the resolution is 4 pixels), and for the test samples used here, this is a fraction of the repeating horizontal fabric structure pattern in the image, and likely to produce irregular results. As the analysis scale approaches the fabric inter-yarn pitch, it is expected that the wavelet analysis should be able to best discriminate between an unpilled image of the fabric and a pilled image. The results for the two test image series presented here suggest that analysis scales related to integer multiples of the fabric inter-yarn pitch yield the best discrimination between pilling levels. Similar results where obtained repeating the analysis using the vertical ($cD_n^v$) and diagonal ($cD_n^d$) detail coefficients. For both the two test image series presented here analysis using $cD_n^h$ produced the widest range in $SDcD_n^o$, though the ‘best’ choice of $cD_n^o$ is likely to be dependent on which $cD_n^o$ analysis scale best matches the fabric inter-yarn pitch in that direction, which in turn, will be dependent on the orientation of the fabric test sample.

For the case of the 1840 double jersey series, it can be seen that poorest ability of the scale five analysis to discriminate between pilling levels occurs at low levels of pilling intensity, and this is perhaps the result of the minor changes in pilling apparent in images 3, 4 and 5 (compared to images 1 and 2) of this standard test series. For the case of the 1842 woven series, it can be seen that poorest ability of the scale five
analysis to discriminate between pilling levels occurs at high levels of pilling intensity, and this is perhaps the result of the minor changes in pilling apparent in images 1, 2 and 3 (compared to images 4 and 5) of this standard test series. As would be expected, the result obtained and the ability of the proposed method to discriminate between levels of pilling intensity will be greatly dependent on the reference test images used to develop the calibration curve.

Optimization of Analysis Method

While the absolute size of the range of $SDcD_n^o$ is important, in the context of ranking subject images against a standard set, the ability to discriminate between the successive pilling intensities represented by successive test images is also important. If a calibration curve that is derived from a particular analysis scale has a large range between the extremes of pilling, but has a small range between one or more of the adjacent pilling ratings, then it will make it difficult to accurately discriminate subject images near that level of pilling. So, uniformity of the ranges of $SDcD_n^o$ between adjacent levels of pilling is also a desirable factor to look for. For a given set of reference pilling test images, at a given analysis scale, we propose a discrimination factor that is given by:

$$\frac{\text{Step}_{\text{min}} \times \text{Range}}{\text{Step}_{\text{max}}}$$  \hspace{1cm} (1)

where $\text{Step}_{\text{min}}$ is the minimum range of $SDcD_n^o$ between adjacent levels of pilling, $\text{Step}_{\text{max}}$ is the maximum range of $SDcD_n^o$ between adjacent levels of pilling, and $\text{Range}$ 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.
As noted above, there are no clear rules for selecting the ‘best’ wavelet for a particular analysis application. A heuristic technique of analyzing sample data with a range of candidate wavelets and applying selection criteria to identify the optimal analysis wavelet is described in the literature [7] [17]. To identify an optimal analysis wavelet and complementary analysis scale for a given set of reference pilling test images, based on $SDcD_n^h$, the authors propose the following heuristic procedure:

1. for the set of reference pilling test images, examine the horizontal intensity of the un-pilled image at a number of vertical positions in the image to observe the characteristic variations;
2. identify a number of candidate analysis wavelets that have a similar form/appearance to the un-pilled variations in horizontal intensity of the un-pilled image;
3. for each of the candidate analysis wavelets, perform the 2DDWT multiresolution analysis to the maximum feasible depth of analysis scale on all images in the set of reference pilling test images;
4. at each analysis scale, record the range of $SDcD_n^h$;
5. for any analysis scale that produces a set of $SDcD_n^h$ that increase monotonically with increasing pilling intensity, compute the ranges of $SDcD_n^h$ between successive test images, and the overall range of $SDcD_n^h$ between the images for minimum and maximum pilling intensity;
6. using these results, compute the discrimination factor given by Equation 1 – the wavelet and analysis scale that yield the largest discrimination factor are the optimal candidates as the basis for automatic evaluation of further sample pilling images against the reference set.
This optimization method was applied to the 1840 double jersey standard pilling test series from James H. Heal & Company Limited - see Figure 1. The test images were prepared as previously described and scanned with 256 levels of gray (0 = black and 255 = white). Figure 5 shows typical plots of horizontal image intensity variation at three vertical points in the un-pilled test image 5 – the horizontal axis represents number of pixels from the left edge of the image, and the vertical axis represents pixel gray scale intensity. The horizontal fabric yarn weave pattern with a pitch of approximately 8 pixels is apparent.
Figure 5. Typical horizontal image intensity variation for un-pilled 1840 double jersey test image – pixels from left edge of image versus gray scale image intensity.

The Matlab software package [21] was used to perform the 2DDWT analysis. The Matlab package includes a Wavelet Toolbox [22] that provides a range of pre-defined wavelets that can be used as the basis for analysis. Using the Matlab wavelet visualization feature, a number of candidate analysis wavelets with a similar form/appearance to the un-pilled horizontal image intensity profiles shown in Figure 5 were chosen. Figure 6 shows the visualization of the chosen analysis wavelets. The Haar wavelet was also included for comparison with the analysis performed previously.
(a) Haar wavelet (= Daubechies wavelet order 1)

(b) Daubechies wavelet order 2

(c) Daubechies wavelet order 3

(d) Symlet wavelet order 4

(e) Coiflet order 1
As noted previously, the multiresolution decomposition analysis process reduces the size of the image by three quarters at each step. Hence, there is a maximum feasible depth of analysis that depends on both the minimum linear dimension of the image (in pixels) and the ‘support width’ of the analysis wavelet. The support widths for the chosen analysis wavelets are shown on the horizontal axes in the visualizations presented in Figure 6 – the larger the wavelet support width, the larger the number of pixels it requires to operate and, hence, the lower the number of analysis scales that can be performed until the image dimensions have been decimated to the minimum feasible size. This feature will be apparent in the following results, where the Haar wavelet with a support width of 1 can yield a deeper (more scales of) analysis than other wavelets that have wider support widths.

When the wavelet analysis was performed on the standard pilling test series it was found that at least one analysis scale for each of the chosen analysis wavelets produced a set of $SDcD_n^h$ that increased monotonically with increasing pilling intensity and hence, all of the chosen analysis wavelets were candidates for use in the development of a pilling intensity calibration curve. For the chosen analysis wavelets...
Tables I to III show the following results for analysis scales that produced monotonically increasing $SDcD^h_n$:

- maximum number of scales of analysis possible;
- $SDcD^h_n$ for each of the five test images;
- the minimum and maximum ranges of $SDcD^h_n$ between successive pairs of test images;
- the overall range of $SDcD^h_n$ between the images for minimum and maximum pilling intensity; and
- the computed discrimination factor based on Equation 1.

Table I. Results for Haar analysis wavelet (maximum analysis depth = 8 scales).

<table>
<thead>
<tr>
<th>Pilling intensity</th>
<th>$SDcD^h_1$</th>
<th>$SDcD^h_4$</th>
<th>$SDcD^h_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (minimum)</td>
<td>71.43</td>
<td>51.99</td>
<td>71.73</td>
</tr>
<tr>
<td>4</td>
<td>74.30</td>
<td>55.99</td>
<td>75.06</td>
</tr>
<tr>
<td>3</td>
<td>79.49</td>
<td>64.64</td>
<td>83.07</td>
</tr>
<tr>
<td>2</td>
<td>81.55</td>
<td>83.03</td>
<td>100.40</td>
</tr>
<tr>
<td>1 (maximum)</td>
<td>91.63</td>
<td>96.24</td>
<td>152.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum range $SDcD^h_n$</th>
<th>2.06</th>
<th>4.00</th>
<th>3.33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum range $SDcD^h_n$</td>
<td>10.08</td>
<td>18.39</td>
<td>52.10</td>
</tr>
<tr>
<td>Total range $SDcD^h_n$</td>
<td>20.20</td>
<td>44.25</td>
<td>80.77</td>
</tr>
<tr>
<td>Discrimination factor</td>
<td>4.13</td>
<td>9.62</td>
<td>5.16</td>
</tr>
</tbody>
</table>
Table II. Results for Daubechies order 2, Daubechies order 3 and Symlet order 4 analysis wavelets.

<table>
<thead>
<tr>
<th>Analysis wavelet</th>
<th>Db order 2</th>
<th>Db order 3</th>
<th>Sym order 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum analysis depth</td>
<td>7 scales</td>
<td>6 scales</td>
<td>6 scales</td>
</tr>
<tr>
<td>Pilling intensity</td>
<td>$SDcD_4^h$</td>
<td>$SDcD_4^h$</td>
<td>$SDcD_4^h$</td>
</tr>
<tr>
<td>5 (minimum)</td>
<td>67.55</td>
<td>62.25</td>
<td>67.50</td>
</tr>
<tr>
<td>4</td>
<td>70.90</td>
<td>64.00</td>
<td>79.34</td>
</tr>
<tr>
<td>3</td>
<td>72.40</td>
<td>78.99</td>
<td>81.12</td>
</tr>
<tr>
<td>2</td>
<td>85.45</td>
<td>89.37</td>
<td>94.08</td>
</tr>
<tr>
<td>1 (maximum)</td>
<td>106.38</td>
<td>101.30</td>
<td>105.05</td>
</tr>
<tr>
<td>Minimum range $SDcD_4^h$</td>
<td>1.50</td>
<td>1.75</td>
<td>1.78</td>
</tr>
<tr>
<td>Maximum range $SDcD_4^h$</td>
<td>20.93</td>
<td>14.99</td>
<td>12.96</td>
</tr>
<tr>
<td>Total range $SDcD_4^h$</td>
<td>38.83</td>
<td>39.05</td>
<td>37.55</td>
</tr>
<tr>
<td>Discrimination factor</td>
<td>2.78</td>
<td>4.56</td>
<td>5.16</td>
</tr>
</tbody>
</table>

Table III. Results for Coiflet order 1, Reverse Biorthogonal order 2.2 and Reverse Biorthogonal order 2.4 analysis wavelets.

<table>
<thead>
<tr>
<th>Analysis wavelet</th>
<th>Coif order 1</th>
<th>RBio order 2.2</th>
<th>RBio order 2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum analysis depth</td>
<td>6 scales</td>
<td>6 scales</td>
<td>5 scales</td>
</tr>
<tr>
<td>Pilling intensity</td>
<td>$SDcD_4^h$</td>
<td>$SDcD_4^h$</td>
<td>$SDcD_4^h$</td>
</tr>
<tr>
<td>5 (minimum)</td>
<td>70.96</td>
<td>50.34</td>
<td>45.38</td>
</tr>
<tr>
<td>4</td>
<td>79.45</td>
<td>57.10</td>
<td>50.32</td>
</tr>
</tbody>
</table>
It is observed that, other than for the Haar wavelet, only analyses at scale four produced a monotonically increasing range in $SDcD_n^h$. At analysis scale four the original fabric image has been decimated four times, hence each pixel in the scale four approximation of the original image represents eight pixels in the original image, which coincides with the fabric inter-yarn pitch for the test images used in this analysis. Analysis with a range of wavelet families suggests that, generally, only when the analysis scale closely matches the fabric inter-yarn pitch will a monotonically increasing range in $SDcD_n^h$ be produced, and hence will the method be useful for automated classification of pilling intensity. The exception observed is the Haar wavelet, which produced a monotonically increasing range in $SDcD_n^h$ not only when the analysis scale closely matched the fabric inter-yarn pitch, but also at analysis scales immediately adjacent. This may be due to the general ‘square wave’ form of the Haar wavelet, which gives it a morphological similarity to a wider range of source data than the more specialized and distinct forms of the other chosen analysis wavelets. It is noted that while the Haar wavelet produced monotonically increasing ranges in $SDcD_n^h$ at analysis scales adjacent to the best match to the fabric
inter-yarn pitch, these adjacent analysis scales were not as good at discriminating between successive pilling intensities as the analysis scale that best matched the fabric inter-yarn pitch.

Interestingly, it is observed that the variation in the total ranges of $SDcD^h_4$ for all the chosen analysis wavelets is comparatively small, with a mean value of 37.23 and standard deviation of 4.21. However, based on the computed discrimination factors, the uniformity of the ranges of $SDcD^h_4$ for the chosen analysis wavelets varies widely and, hence, so does the ability of the chosen analysis wavelets to provide a basis for establishing a calibration curve for relating pilling intensity to $SDcD^h_n$.

The analysis wavelet with the largest discrimination factor for the 1840 double jersey test image series used in this trial was the Reverse Biorthogonal wavelet order 2.4, with a discrimination factor of 12.45. Interestingly, this was followed closely by the Haar wavelet at analysis scale four, with a discrimination factor of 9.62. The computed discrimination factors for all other chosen analysis wavelets were significantly lower. This suggests that, in the absence of identifying an optimal analysis wavelet by the heuristic methodology described, the Haar wavelet may be an acceptable default choice that provides reasonable discrimination performance, due to its square wave form having a general similarity to the repetitive structure found in the data from fabric images.

Discussion

Other work currently in progress to evaluate the proposed analysis method indicates that the method is:
robust to small horizontal and/or vertical translations of the image under analysis – this would be expected, as neither the orientation of the underlying pattern of the fabric structure nor the bulk of the pilling details are altered;

robust to significant variations in the brightness of the image under analysis – this would be expected as changes in image brightness level affect the entire image in the form of an offset and/or scaling of the image data, which is a low frequency effect that principally impacts on the wavelet approximation coefficients and not the detail coefficients (which represent higher frequency components in the image) employed in the proposed method;

sensitive to rotation of the image under analysis – this would be expected as image rotation changes the effective fabric inter-yarn pitch in any given direction and may significantly change the pilling details in the image area; and

sensitive to dilation of the image under analysis – this would be expected as scaling of the image due to changes in image magnification and/or distance between the camera and the fabric sample will alter the apparent inter-yarn pitch.

This suggests that as long as precautions are taken to ensure fabric test sample imaging is performed under consistent conditions of weave/knit pattern alignment, apparent inter-yarn pitch and general illumination conditions, then the proposed method will yield repeatable results.

Further investigation planned to evaluate the proposed analysis method includes:

investigation of the robustness of the proposed method to other changes in image characteristics such as variations in fabric coloring;

investigation of other statistical properties of the distribution of $cD_n^o$ from multiresolution analysis of pilling images that provide a measure of the ‘spread’ of coefficients, such as the median absolute deviation and mean absolute deviation,
to determine if they are better measures of relative pilling intensity than the
standard deviation;

- application of the proposed method to other series of standard pilling evaluation
test images commonly used internationally [16], to confirm the wider applicability
of the proposed method; and

- comparison of the proposed method against human experts in trials of pilling
evaluation, as documented in the literature for other pilling evaluation techniques
based on image processing [2, 10].

Conclusions

A new method of frequency domain analysis based on the two-dimensional
discrete wavelet transform (2DDWT) to objectively rate the pilling intensity in
sample images was described. A preliminary evaluation of the proposed method
based on analysis of two series of standard pilling evaluation test images was
presented. The initial results obtained suggest that the proposed method is feasible,
and that the ability of the method to discriminate between levels of pilling intensity is
dependent on the wavelet analysis scale being closely matched to the fabric inter-yarn
pitch. A heuristic method was also presented for the optimal selection of an analysis
wavelet and associated analysis scale. The results obtained suggested that the Haar
wavelet may be a reasonable basis for analysis due to its square wave structure
approximating the weave/knit fabric structure.
Acknowledgement

The standard pilling test series images in Figure 1 and Figure 2 are the copyright property of James H. Heal & Company Limited and reproduced with their permission.

Literature Cited


