CHARACTERIZING CONVOLUTIONS IN COTTON FIBER USING IMAGE ANALYSIS

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Abstract

An image analysis procedure was developed to quantify morphological characteristics of convolutions in individual cotton fibers without pre-tensioning or orientation requirements. The image of each fiber was captured by a PC-based color imaging system using a conventional microscope. Ends of individual cotton fibers were glued on a microscope slide without any tension or straightening. A modified watershed technique was implemented to identify individual convolution segments, which were defined as sections of the fiber bordered by two neighboring convolutions. Length, area and perimeter of each convolution segment were measured directly from the image. Average width, shape factor and number of convolution segments in mm were calculated from the measured parameters. The performance of the image analysis algorithm was compared with visual inspection for number and position of convolution segments in three different varieties of cotton. The image analysis results agreed with visual inspection in 89.6% of the tested images.

Introduction

There have been several studies on characterizing convolutions of cotton fibers and relating convolution characteristics to fiber quality. As early as 1923, Denham (1923) suggested that convolutions might exercise a profound influence on the spinning qualities of fibers. Clegg and Harland (1924) counted the number of convolutions and reversals using a microscope. Meredith (1951; 1953) defined the ratio of the ribbon width to the pitch of the convolution as the convolution angle and found that the convolution angle and the Pressley strength were highly correlated. Betrabet et al. (1963) reported that the fiber bundle strength was highly correlated with the fibrillar orientation. Hebert (1975) and Duckett (1977) also confirmed that fiber tenacity and convolution angle have high negative correlation.

Convolutions can be measured by an optical microscopic method (Clegg and Harland,1924; Meredith, 1953). Duckett and Cheng (1972) introduced a technique to detect cotton fiber convolutions by a device which allowed azimuthal monitoring of reflected light. They reported that the new technique was as simple as conventional X-ray orientation techniques and faster than microscope techniques. All these methods were time-consuming and laborious to collect individual convolution data.

Thibodeaux and Evans (1986) used an image analysis to measure cotton fiber maturity by measuring convolution characteristics. Individual cotton fibers were arrayed longitudinally by pulling them straight and gluing the ends to a standard microscope slide. Although scanning fibers longitudinally is superior to the cross-sectioning approach because of its higher resolution and less chance of introducing various errors, pulling the cotton fiber straight may change the shape of a convolution and possibly cause a partial or complete elimination of a convolution. Xu et al. (1992, 1993), on the other hand, asserted that it is more accurate to examine cotton lumens and wall thicknesses from cross-sectional views than from longitudinal view, and developed image analysis techniques for fiber cross-sectional shape analysis to quantify maturity and related characteristics.

Deussen (1990) pointed out that today's high speed and automated cotton processing equipment requires knowledge of the individual and collective effects of raw-material properties on processing behavior. Although HVI systems and conventional laboratory methods are being used for bundle tests, the textile industry can benefit from the study of single fiber properties as well as the data from bundle tests. But single fiber testing is time-consuming and laborious. Therefore, an effective tool for automatic measurement of single fiber properties with simple sample preparation is needed.

The purpose of this study was to develop an image analysis technique to quantify morphological characteristics of convolutions in a single cotton fiber without pre-tensioning or orientation requirements.

Imaging Equipment

The image processing hardware used in this study included a MATROX IMAGE-1280 imaging board with IMAGE-CLD color digitizer module from Matrox Electronics Systems Ltd., installed on a 50 MHz 80486 microcomputer. The imaging board has a 1280x1024 spatial resolution and three 8-bit RGB digitizers. Color images of cotton fibers were captured by SONY DXC 930 color camera with a three-chip CCD image sensor, which was mounted on a Zeiss microscope with 10X objective lens through LA-CS50 optical relay from Century Precision Industries, Inc. The ends of individual cotton fibers were glued on a conventional microscope slide without any tension and

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illuminated with the back-light installed in the microscope. Color images of cotton fibers were captured at a 512x480 spatial resolution, and displayed on a Sony Multiscan 17se high resolution RGB monitor. The image analysis algorithms developed in this study were programmed in the C Interpreter of the Visilog 4.13 from Noesis Vision, Inc.

Image Analysis

Definition of Convolution Segment

Convolutions in a cotton fiber are developed during the collapse of the tubular fiber as it dries. Meredith (1951) defined a convolution as a twist of the fiber through 180° about its axis. The longitudinal image of a convoluted fiber looks like a twisted ribbon with a series of bobbin-like segments, where the shape of the bobbin-like segments is affected by how much the fiber is convoluted. A convolution is defined as a border between two bobbin-like segments. In this study, the bobbin-like segment which was bordered by two neighboring convolutions was defined as a *convolution segment*. According to this definition, a convoluted fiber can be considered as a chain of convolution segments.

Traditionally, convolutions have been characterized by the number of convolutions per unit length, convolution angle, and convolution pitch which is the distance between two neighboring convolutions (Clegg and Harland, 1924; Meredith, 1951; Betrabet et al., 1963). In this study, convolutions were characterized by the number of convolution segments per mm, and the size and shape of each individual convolution segment.

Image Preprocessing

The image preprocessing procedure consisted of image segmentation, separation of convolution segments by a watershed technique, and skeleton operation. The color image of a cotton fiber had a spatial resolution of 512x480 with 256 intensity levels for each red, green and blue components. This color image was converted into a binary image by an automatic thresholding technique. Intensity of each pixel in the input color image with red, green and blue components that satisfy following relationships were set to **1** (white) in the output binary image:

$$m_R - 3\sigma_R - 0.5 \leq I_R \leq m_R + 3\sigma_R + 0.5$$
$$m_G - 3\sigma_G - 0.5 \leq I_G \leq m_G + 3\sigma_G + 0.5$$
$$m_B - 3\sigma_B - 0.5 \leq I_B \leq m_B + 3\sigma_B + 0.5$$

where, I: pixel intensity of each color component
m: mean intensity value of each color component
σ: standard deviation of intensity of each color component subscript R, G, B: red, green, and blue component, respectively

All the other pixels were set to **0** (black) in the output binary image. After this operation, the image of cotton fiber was shown as white on a black background. To clean background noise in the image and to eliminate artifacts inside the fiber, closing and opening operations were applied next. The closing operation fills small holes presented inside an object, connects proximate particles, and eliminates small details by smoothing the boundary from the outside. The opening removes small particles and cleans up small details on the boundary such as peaks and isthmuses.

After the binary segmentation, a modified watershed technique (Vincent and Soille, 1991; NOESIS, 1991) was used to separate individual convolution segments in a cotton fiber. The watershed technique is analogous to finding crest lines dividing two disconnected basins in a mountain range. Fig. 1 shows the separation of a cotton fiber into convolution segments by the watershed technique. Fig. 1(a) shows the longitudinal projection of a typical cotton fiber, and the distance from the center of fiber to the fiber boundary is plotted in Fig. 1(b). This extra step in software eliminates a physical orientation requirement that the fiber has to be absolutely straight. Without this extra step, the fiber has to be pulled straight before mounting on the microscope slide, and the tension in the fiber may change the size and shape of the convolutions.

The next step was to find local minima in the fiber. First, each pixel in the image was assigned a grey level equal to the distance from the boundary of the fiber. Successive erosion operations were performed on this grey level image until only the points with the highest grey level value in the regions remained. The remaining points were mapped vertically down onto the boundary of the fiber to find local minima. To eliminate excessive minima due to irregular shape of the fiber boundary, such as the region between watersheds B and C in Fig. 1(b), the points with the highest two grey levels of each region were merged into one modified minimum. The crest lines, or watersheds, were then found by a simulation of progressive flooding from the modified minima. The watershed was defined as the point (or lines) where two separate basins join as the water rises. In the cotton fiber, watersheds denoted convolutions, and the region between two convolutions was defined as a convolution segment.

Fig. 2. shows the result of the modified watershed algorithm. Fig. 2(a) shows the original cotton fiber, and the different shades in Fig. 2(b) shows the identified convolution segments. In Fig. 2(c), two segments at the either ends of the fiber were removed to exclude incomplete segments, and only the remaining whole segments in the figure were used in subsequent analysis. Since the lengths of the curved segments cannot be measured directly from this image, a skeleton of the cotton fiber was obtained by successively thinning and pruning the image until it became one-pixel-thick line segments as shown in Fig. 2(d). The lengths of the segments were then measured as one half of the perimeter of each line segment.

Image Analysis and Measurements

To characterize convolution segments, the area and perimeter of each convolution segment were measured from the image in Fig. 2(c). The area of each segment was measured by counting the number of pixels belonging to each segment and multiplying scale factors. The horizontal and vertical scale factors were calibrated before the measurement and were 1.087 µm/pixel and 0.8772 µm/pixel, respectively. The length and perimeter were measured by the Crofton formula (NOESIS, 1991), which counts the intercept numbers along major directions and corrects for non square pixels. The length of a convolution segments means the pitch of the convolution in the traditional definition.

The number of convolution segments per millimeter, average width, and the shape factor of each segment were derived from the area, perimeter and length as follows

$$N = 1000/L_a \tag{1}$$

$$W_a = A/L \tag{2}$$

$$F_s = P^2/(4\pi A) \tag{3}$$

where, N: number of convolution segments per millimeter

L_a: average length of convolution segments in a fiber (µm)
W_a: average width of a convolution segment (µm)
A: area of a convolution segment (µm^2)
L: length of a convolution segment (µm)
F_s: shape factor
P: perimeter of a convolution segment (µm)

The shape factor measures the elongation of a convolution segment. The shape factor F_s is minimal and equal to 1 for a circle. An elongated segment has a high shape factor. The shape factor has nonlinear negative relationship with the convolution angle - the larger the shape factor, the smaller the convolution angle. The maximum width of a convolution segment, W_m, can be estimated as below if a convolution segment is assumed as an ellipse:

$$W_m = 4A/\pi L \tag{4}$$

Validation Test

Three different varieties of cotton, DPL ACALA 90, ACALA MAXXA SJV, and PAYMASTER HS 26, were used for validation test. Ninety cotton fibers, thirty fibers from each variety, were randomly selected from each cotton. Each single fiber was mounted on a microscope slide glass to capture a longitudinal image of the cotton fiber. Because pulling the fiber may change the shape of convolutions, the ends of the fiber were glued to the slide without any tension. Three images were captured from each fiber for convolution measurements - from the bottom, middle and top parts of each fiber. The modified watershed algorithm was applied to each image to identify each convolution section. The performance of the image analysis algorithm was compared with visual inspection for number and position of convolution segments in each image. Visual inspection was performed by a person who is familiar with convolutions in cotton fiber.

Table 1 shows the results of convolution recognition by the watershed technique when compared with visual inspection. Among the total of 270 images, 242 images, or 89.6%, were correctly recognized by the watershed technique. Number of convolutions was miscounted in 23 images, or 8.5%. In five images, or 1.9%, the number of convolutions was correctly identified but their positions were different from where visual inspection indicated. Variation in recognition accuracy among varieties was very small.

Table 2 shows the distribution of errors in counting convolutions by the watershed technique. Among the 23 miscounted images, 18 images had the error of one convolution overcounted or undercounted, and only two images had errors of more than three convolutions. For some of these miscounted convolutions, the collapse of the fiber was hardly visible and ambiguous. If the counting error of one convolution was considered acceptable, it could be said that the watershed technique successfully identified 260 images out of 270 total images with a success ratio of 96.3%.

Table 3 shows the morphological properties of convolution segments in the tested cotton fibers measured by image analysis algorithm developed in this study. It was observed that there were large deviations among the tested fibers. For example, the length of convolution segments ranged from 42.8 to 260.1 µm for DPL ACALA 90, from 47.4 to 291.3 µm for ACALA MAXXA SJV, and from 40.5 to 224.6 µm for PAYMASTER HS 26. Despite the variations within the varieties, statistical analysis indicated that there were highly significant differences between varieties for length, perimeter, shape factor and number of convolution segments per mm. Area, average width and maximum width were also significantly different between varieties with 95% confidence.

Table 3 also shows the results of Duncan's multiple range test for each parameter with respect to variety. The test showed that these three varieties can be classified into two separate categories by length, perimeter, width, and the shape of the convolution segments. DPL ACALA 90 and ACALA MAXXA SJV had high shape factors and low number of convolution segments per millimeter, whereas PAYMASTER HS 26 had a low shape factor and high number of convolution segments per millimeter. It should be noted that the number of convolutions per mm was not calculated as the reciprocal of the average length of all convolution segments, but as the average number of convolutions per mm calculated for each fiber.

Summary and Conclusion

An image analysis procedure was developed to quantify morphological characteristics of convolutions in a single cotton fiber without pre-tensioning or orientation requirements. The image of each fiber was captured by a PC-based color imaging system using a conventional microscope. Ends of individual cotton fibers were glued on a microscope slide without any tension or pulling it straight. The color image was converted to a binary image by automatic threshold, and a modified watershed technique was implemented to identify individual convolution segments in the fiber. Length, area and perimeter of each convolution segment were measured directly from the image. Average width, shape factor and number of convolution segments in mm were calculated from the measured parameters.

The performance of the image analysis algorithm was compared with visual inspection for number and position of convolution segments in three different varieties of cotton. Among the total of 270 images, 242 images, or 89.6%, were correctly recognized by the watershed technique. Number of convolutions in 260 images, or 96.3%, were within one convolution from the visual inspection result. In five images, or 1.9%, the number of convolutions were correctly identified but their position was different from where visual inspection indicated. Variation in recognition accuracy among varieties was very small.

Morphological analysis showed that the deviations among the tested fibers were much greater than the difference between the variety. Despite the variations within the varieties, statistical analysis indicated that there were highly significant differences between varieties for length, perimeter, shape factor and number of convolution segments per mm. Duncan's multiple range test showed that the three varieties can be classified into two separate categories by length, perimeter, width, and the shape of the convolution segments. DPL ACALA 90 and ACALA MAXXA SJV had high shape factors and low number of convolution segments per millimeter, whereas PAYMASTER HS 26 had a low shape factor and high number of convolution segments per millimeter.

Disclaimer

Mention of specific products is for information only and not to the exclusion of others that may be suitable.

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Table 1. Results of convolution recognition by the watershed technique.

Variety	Correct Recognition	Counting Error	Positioning Error	Total
DPL ACALA 90	79	10	1	90
ACALA MAXXA SJV	81	7	2	90
PAYMASTER HS 26	82	6	2	90
Total	242	23	5	270

Table 2. Distribution of counting errors by the watershed technique.

Variety	Differences in number of convolution*					
	-4	-3	-2	-1	+1	Total
DPL ACALA 90	0	1	1	7	1	10
ACALA MAXXA SJV	0	0	1	6	0	7
PAYMASTER HS 26	1	0	1	3	1	6
Total	1	1	3	16	2	23

* Negative and positive numbers designate numbers of undercounted and overcounted convolutions in each image, respectively.

Table 3. Average morphological properties of convolution segments in the tested cotton fibers.

	Variety		
Parameter	DPL Acala 90	Acala Maxxa SJV	Pay MasterHS26
Length, µm	108.46 a†(26.56)‡	107.23 a(17.60)	90.56 b(18.22)
Area, µm^2	1850.26 ab(481.37)	1905.91 a(399.96)	1642.06 b(399.44)
Perimeter, µm	255.88 a(54.74)	254.92 a(37.96)	220.46 b(39.34)
Average width, µm	16.92 b(1.31)	17.61 ba(1.58)	18.02 a(2.27)
Maximum width, µm	21.67 b(1.81)	22.54 ba(1.97)	23.05 a(2.91)
Shape Factor	2.86 a(0.53)	2.76 a(0.38)	2.41 b(0.40)
No. of convolution segments per mm	9.66 b(2.08)	9.58 b(1.62)	11.43 a(2.04)

† Averages followed by the same letter are not significantly different at 95% confidence level using Duncan's Multiple Range Test.

‡ Values in parenthesis indicate standard deviations.

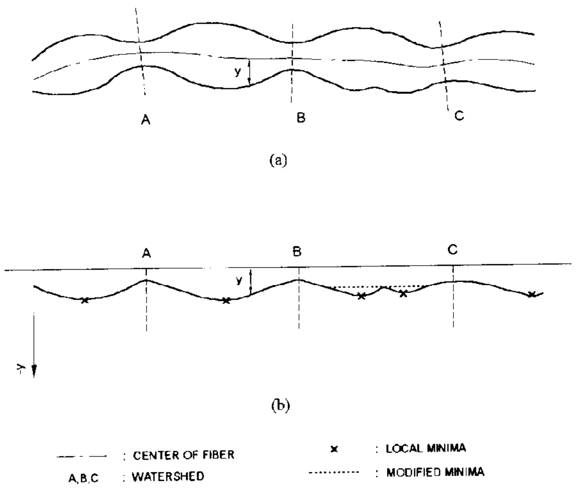

Figure 1. Identification of convolution segments by watershed technique. (a) longitudinal projection of a cotton fiber; (b) distance from the center to fiber boundary.

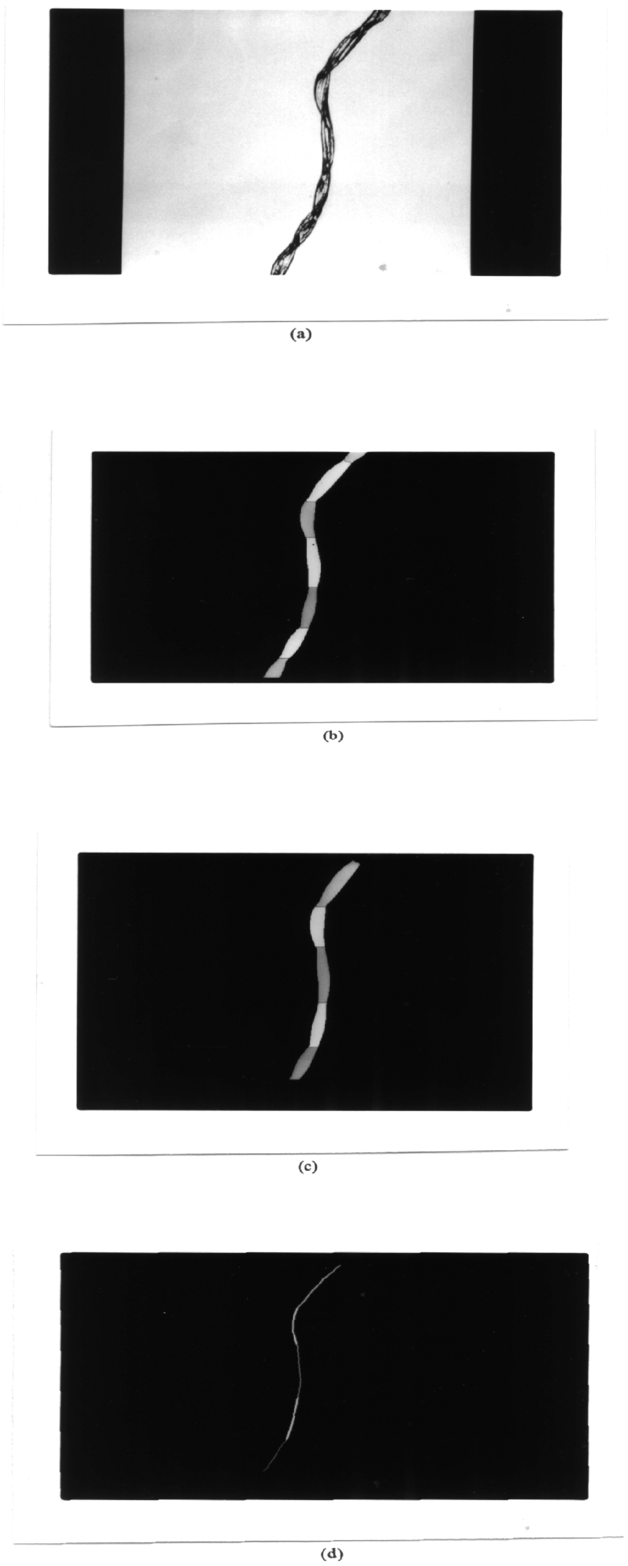

Figure 2. Images of cotton fiber processed by watershed technique. (a) original image; (b) after segmentation and identification of convolution segments; (c) after two end segments removed; (d) skeleton of the fiber for length measurement.