SINGLE COTTON FIBER CHARACTERIZATION USING A LASER DIFFRACTION SYSTEM

Ayodeji Adedoyin
Changying Li
Biological and Agricultural Engineering Department, University of Georgia
Tifton, Georgia
Mike D. Toews
Entomology Department, University of Georgia
Tifton, Georgia

Abstract

The fineness and maturity of a cotton fiber is determined by its cross sectional perimeter and area. However, measuring fiber cross sectional perimeter and area is an extremely tedious and challenging task. This paper presents an alternative approach to measure fiber longitudinal width using Fraunhofer diffraction patterns, which can be used to estimate fiber fineness and maturity. We designed a laser diffraction system, developed a software program to denoise and process diffraction patterns, and tested the system on a uniform iron wire and individual cotton fibers from ten bales. The width of the iron wire measured by our system was 25.43 µm (0.1% different from the nominal value) with a standard error of mean of 0.01 µm. Cotton fiber width measured by the laser diffraction system could differentiate among ten cotton bales, which was in accordance with their relative differences in the fineness values. This simple, replicable, and relatively inexpensive optical system could be used for single fiber longitudinal profile characterization and cotton fineness and maturity estimation.

Introduction

Fiber fineness is a measure of the area of the fiber wall while the maturity (as defined by the maturity ratio) is a measure of the development of fiber wall relative to the perimeter of a fiber (Montalvo 2005; Hequet E. F. et al. 2006). Both parameters are related to the cross sectional area and perimeter of a single fiber. Therefore, the cross sectional measurement of cotton fibers is the most accurate technique to determine the fineness and maturity. The cross sectional method requires that cotton fibers be cut into segments and observed and analyzed using microscopic images (Xu and Huang 2004; Hequet E. F. et al. 2006). In spite of its accuracy, this destructive method is extremely tedious.

Currently, the high volume instrument (HVI) uses the rate of airflow across a bulk sample to indirectly estimate the micronaire which is a function of both the fineness and maturity (Pierce and Lord 1939; Lord 1956). It is based on the assumption that the rate of airflow across the finer fiber samples would be smaller than that across the coarser fiber samples given equal weights of fiber samples because finer fibers have greater surface area (USDA AMS 2001; Montalvo 2005). In one study, the micronaire of a bulk cotton sample was estimated by the scattering spectra measured by a multispectral imaging system (Sui R. et al. 2008). Although the bulk sample measurement is a relatively easy and inexpensive technique, it cannot provide fundamental details about the individual cotton fibers for a more accurate and direct measurement of fineness and maturity.

Several other alternative approaches were reported to measure the fineness and maturity by examining individual fibers. Light-scattering experiments have been developed to determine the optical properties of single cotton fibers and then correlate these properties with cotton fiber fineness (Aslan M. et al. 2003). Cotton fiber quality has also been characterized through electromagnetic scattering by using a laser system at various wavelengths, polarization angles, and scattering angles (Thomasson et al. 2009). An image analysis system was developed to measure ribbon-width (projected fiber width) of individual cotton fibers through longitudinal measurements, although the overlap and occlusion of fibers reduced the accuracy of the measurement (Y. Huang and Xu 2002). To our knowledge, however, no study has been done to measure the longitudinal width of single cotton fibers using the laser diffraction technique. The main advantage of the laser diffraction method is that it does not require that the cotton fibers be cut into segments to measure fiber width or cross-sectional properties of cotton fibers. Segmentation of single fibers could potentially distort the natural shape or structure of the fibers and possibly provide erroneous fiber width values. Another benefit of this approach is that the natural variation such as crimps and convolutions of single cotton fibers can be revealed by scanning multiple points along a single fiber. In addition, the overlap and occlusion in imaging analysis approach is not a problem anymore since each fiber is scanned individually. In this work, we developed a laser optical system that utilizes Fraunhofer diffraction patterns to determine the fiber longitudinal width. Based on the well established Fraunhofer (far-field) diffraction theory, diffraction patterns appear when a monochrome light such as laser passes through a thin slit and the distance between fringes in the diffraction pattern can be used to calculate the diameter of the slit (Hecht 2001). Another foundation of our optical approach is based on Babinet's principle, which states that the diffraction pattern generated by illuminating a single fiber or a slit with the same width should be the same (Tang W. et al. 1999). This optical approach could provide a simple, inexpensive, and fairly accurate technique to determine the ribbon-width of single fibers. The overall objective of this study was to develop an optical system and software program that utilizes the laser diffraction pattern to measure the ribbon-width of single fibers.

Optical System Development

Optical system components

The schematic of the optical system designed and built to study the optical properties of single fibers (including cotton fibers) is shown in Figure 1. The optical system consists of a light source, polarizing lenses (P1), an iris (I1), a single cotton fiber sample holder (S1), a collecting lens (CL) and a linear CCD camera (CCD).

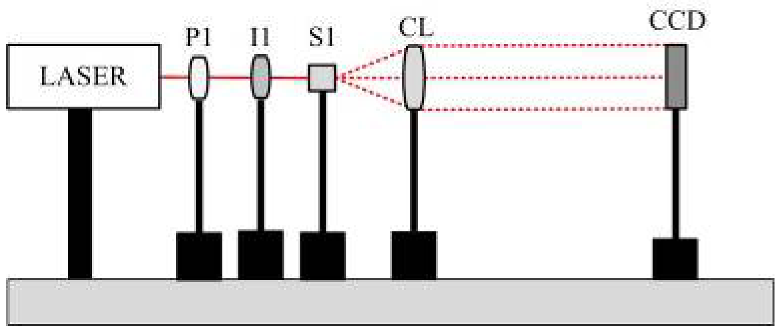

Figure 1. Schematic of optical system used to study the optical properties of single fibers.

The light source used was a 0.8 mW linearly polarized Helium-Neon Laser (HRP008, Thorlabs Inc., Newton, NJ) with a nominal wavelength of 633 nm. The diameter of the laser beam immediately emanating from the light source is approximately 0.57 mm (570 μm) with a beam divergence of 1.41 mrad. In order to prevent the CCD camera from being saturated, a linearly polarizing lens (LPVISB050, Thorlabs Inc., Newton, NJ) was placed behind the laser light source to attenuate its intensity. The intensity of the laser light was controlled (reduced significantly) by rotating the transmission axis of the polarizing lens. The transmission axis of each polarizing lens was marked by the manufacturer. In order to rotate the polarizing lenses a manual rotation mount (RSP05/M, Thorlabs Inc., Newton, NJ) was used. Each polarizing lens was inserted into the manual rotation mount, which had laser engraved scale markings at every 2° increments. In this way the angle of rotation of each polarizing lens can be easily determined. An iris (ID25SS, Thorlabs Inc., Newton, NJ) was placed behind the polarizing lenses and was used to control any stray laser light that may have been generated as a result of placing the polarizing lens behind the laser light source. A single fiber sample holder was designed and built to hold each single fiber in a horizontal orientation and perpendicularly to the propagation of the laser beam. The dimensions of the sample holders were 76.2 mm wide by 38.1 mm long with a 12.7 mm hole punched in the middle of the sample holder. Single fibers were then attached along the reference line across the punched hole by using double sided tape.

In order to scan multiple points along a single fiber, the fiber was attached to the sample holder which was mounted on a manual linear stage (420, Newport, Irvine, CA). The only moveable part of the experimental setup was the manual linear stage and since the sample holder with a single fiber attached was mounted on the linear stage then consequently the fiber could be moved. The traveling distance of the manual stage was 12.7 mm. By moving the manual linear stage the laser light could illuminate multiple points along each fiber. A collecting lens (LB1676-C, Thorlabs Inc., Newton, NJ) with a focal length of 10 cm was placed behind the cotton fiber holder.

A linear CCD camera (TCN-1304-U, Mightex Systems, Pleasanton, CA) was used to capture the diffraction patterns generated as a result of illuminating multiple points along a single fiber. The sensing portion of the CCD camera was able to capture the diffraction pattern by using 3684 pixels. Each pixel size was 8 µm therefore the total length of the sensing portion was approximately 29.5 mm. Although the polarizing lenses were used to attenuate the intensity of the laser light, the CCD camera was still saturated due to the intensity of the center fringe of the diffraction pattern. To prevent saturating the CCD camera, the center portion of the CCD camera was blocked-out with black flocked self-adhesive paper (BFP1, Thorlabs Inc., Newton, NJ). The dimensions of the block out material were about 3 mm wide and 0.381 mm thick.

Sample preparation and data collection

By nature, cotton fibers are convoluted and have crimps along the axis of the fibers, therefore over-stretching a cotton fiber may alter the shape (natural convolutions and crimps) of the fiber. Furthermore, under-stretching a fiber may result in inaccurate results since the laser light may not illuminate all the points along the axis of the fiber. A sub-sample (pinch) of cotton fibers were manually extracted from a 25 g sample from one cotton bale. The sub-samples were combed to separate the cotton fibers and reduce the number of crimps present of the fibers. With the help of a microscope, one end of the fiber was placed on one side of the sample holder and the other side was stretched across the 12.7 mm hole in the sample holder. The system developed and implemented in this work requires that the fibers be perpendicular to the direction of propagation of the laser beam and that each fiber must be held straight to ensure that the laser beam illuminates each point on the fiber. The fiber was straightened across the 12.7 mm hole to be level with the reference line but yet not fully stretched it to distort the natural convolutions on the fiber.

It is well documented that the ribbon-width of cotton fibers is anisotropic (non-uniform) along their axis due to the presence of crimps and convolutions. By scanning multiple points along each single cotton fiber their anisotropic nature may be studied and analyzed. Based on the design of the single fiber sample holder, the length of each fiber analyzed was approximately 12.7 mm. Each single fiber was illuminated by the laser light at approximately ninety (90) evenly distributed points with 141 µm spacing interval. It must be mentioned that the points illuminated were overlapping and this was done to capture as much as possible about the optical properties of single cotton fibers.

Once the sample holder with an attached fiber was secured on the manual linear stage, the sample holder was adjusted so that the laser light illuminated the leftmost portion of the single fiber. The diffraction pattern generated from this position was recorded as position 1. By moving the barrel of the manual linear stage, the fiber was shifted by a distance of approximately 141 µm to record the diffraction pattern of the next position. This process was repeated until the entire fiber was scanned and this resulted in about ninety diffraction patterns. It took roughly 8-10 minutes to scan 90 points alone one single fiber. If a motor is used to move the fiber automatically, which will be the goal for the next stage of this study, the speed could be significantly improved.

Software

The software was developed by using the MATLAB (Mathworks, Natick, MA). The function of the software include: denoising of the raw diffraction data, calculating dark fringes automatically, and managing data. Fiber width can be calculated by the following equation:

$$d = \frac{m\lambda f}{X_2 - X_1}$$

where d is the fiber width. $m = \pm1, \pm2, \pm3, \ldots \lambda$ is the wavelength of the monochromatic laser light, and f is the focal distance of the collecting lens used. A positive *m* value is for fringes located on the right hand side of the blocked-out region and negative *m* values represent fringes located on the left hand side of the blocked-out region. X_2-X_1 is the distance between two dark fringes.

Preliminary tests showed that the fiber width computed from the first (L1 and L2) and second (L3 and L4) dark fringes were comparable, although the second dark fringes were not observed in every scanning point. For simplicity, only the fiber ribbon-width computed from the first dark fringes were reported and discussed thereafter.

Experiment

Testing of uniform iron wires

The development of any new system requires that a validation step be performed to describe the accuracy of the system. Since the true fiber width values from cotton fibers were almost impossible to obtain, a uniform iron wire (SPIR-001-50, Stamford, CT) with known diameter (25.4 µm) was used to validate our system. A typical diffraction pattern generated from illuminating the iron fibers is illustrated in Figure 2, which shows a diffraction pattern with multiple higher order fringes on both sides of the blocked-out region. Using such diffraction patterns, the threshold for locating valid second order dark fringes was set as 0.2 mm. The threshold for determining which diffraction patterns were symmetric about the blocked-out region was determined as 0.1 mm based on preliminary tests. The text insert in Figure 2 shows the difference between the calculated and theoretical middle point of the diffraction was 0.180 mm. Figure 2 also shows that the block-out strip was placed towards the left half of the observation plane and this is observed by a smaller peak value immediately to the left of the middle of the diffraction pattern when compared with the peak on the right hand side of the blocked-out region.

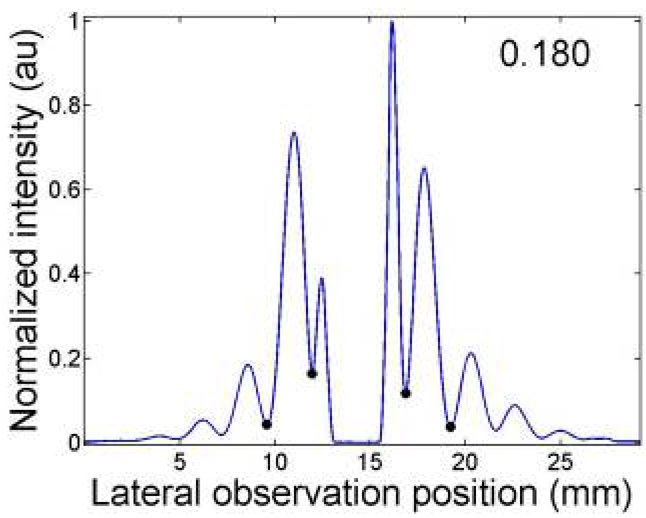

Figure 2. Sample diffraction pattern generated by illuminating a single iron wire.

Figure 3 presents a histogram which shows the distribution of the ribbon-width values of 10 iron wires measured by the optical system. Each iron wire was illuminated at ninety (90) points and therefore, 900 total diffraction patterns were obtained from the 10 iron wires. Of 900 total diffraction patterns, 761 patterns were judged as valid by the pattern processing software (the rest 139 patterns were judged as erroneous and not considered). The overall shape of this histogram follows a normal distribution pattern. The mean value of the iron wire diameter in this histogram was 25.43 µm which is only 0.11% higher than the nominal diameter value (25.40 µm) provided by the manufacturer. Other statistics such as the standard deviation (0.30 µm), standard error (0.01 µm), and coefficient of variation (CV) (1.18%), indicate that the repeatability of the optical system was good in measuring fiber diameter of the iron wire. One potential error source may come from the sample preparation. During sample preparation, wires must be exactly horizontal to avoid the error in measurement. In other words, the iron wires must be exactly placed over the reference line of the sample holder. Slight deviations from the reference line may have contributed diffraction patterns that deviated from the sensing portion of the CCD camera.

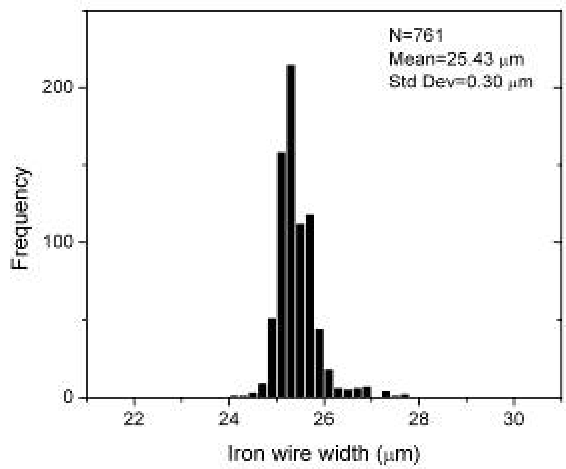

Figure 3. Distribution of ribbon-widths obtained by illuminating iron wires.

Testing of cotton fibers

Cotton samples were provided by the Fiber Research Group at the Fiber and Biopolymer Research Institute (Texas Tech University, Lubbock, TX). Cotton fiber quality parameters (such as AFIS fineness and HVI micronaire) and cross-sectional parameters (perimeter and area) for the 104 cotton bales have already been studied in detail and were available for public use (Hequet E. F. et al. 2006). To layout single fibers for all 104 cotton bales at once would prove to be a very time consuming and tedious task. Therefore, ten cotton bales were selected for our study. They have fineness values covering the full range of what the 104 bales provide. The group consisted of Bales 2684, 3035, 3043, 3054, 3096, 3104, 3138, 3177, 3178, and 3182 with corresponding AFIS fineness values of 144, 163, 156, 161, 160, 173, 170, 167, 177, and 175, respectively.

Figure 4 demonstrates the distribution of cotton fiber width measured by the laser diffraction system for ten cotton bales. Almost all ten bales generally follow a bell shape distribution in their ribbon width measurement with the exception of Bale 2684 which has two peaks in its distribution. Although the general distribution from all ten cotton bales look similar, they vary in their mean values and distribution range as shown in histograms of each bale. The skewness and Kurtosis were used to characterize the symmetry and peakedness of each histogram. Bale 2684 has the smallest mean fiber width (13.32 μm) while Bale 3178 has the largest mean fiber width (15.84 μm). The difference of the fiber width between these ten bales generally reflects the same difference trend in their fineness values measured by the AFIS. Another important observation from these histograms is that shape of the distribution of fiber width is shorter (in counts) and wider (in range) when fibers (such as Bale 2684, 3043 and 3096) are less mature. Conversely, the shape of the fiber width distribution is usually narrower and taller for more mature fibers (such as Bale 3177, 3138, 3104, and 3178) with the only exception of Bale 3182. This is largely because mature fibers are stronger and thicker, have fewer convolutions, and therefore are more uniform in longitudinal width. Within each individual fiber, the smaller values of fiber width may be attributed to the presence of convolutions along the fiber's axis; the larger values of fiber width may be positions along the fiber that are flat and thicker. The large range of the fiber width distribution authentically reflects the anisotropic nature of the cotton fiber.

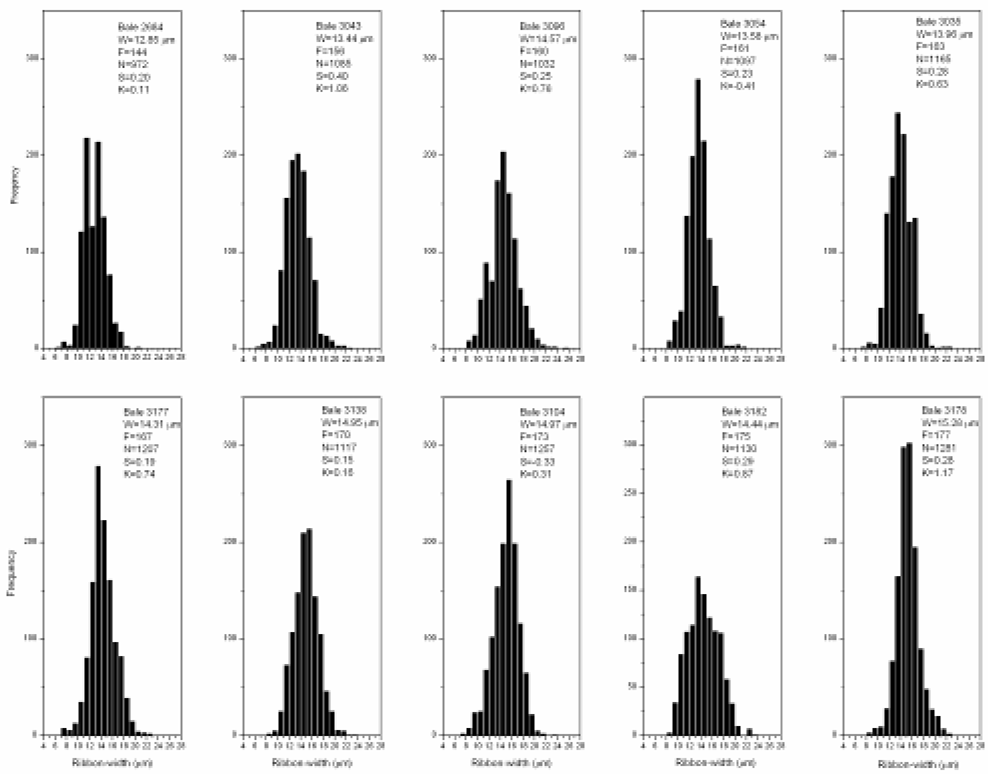

Figure 4. Distribution of fiber ribbon-width measurements of eight cotton bales. W=fiber ribbon-width; F=fiber fineness; N=valid measurements; S=skewness; K=Kurtosis.

The number of valid measurements in each cotton bale varied from N=972 (Bale 2684) to N=1281 (Bale 3178), ranging from 54% to 71% of total 1800 measurements for each bale. This reflects the difficulty in obtaining valid diffraction patterns for every point along the cotton fibers due to fiber crimps and convolution. There is a general trend that the number of valid measurement in each bale increases as the fiber is more mature. Nevertheless, majority of measurements yielded valid diffraction patterns. Almost all distributions are slightly right skewed except Bale 3104 which is slightly left skewed (skewness=-0.33). Given the relative small values of the skewness (0.15-0.40), these histograms are generally symmetric. As for the Kurtosis, most histograms are close to the standard normal distribution with values between zero and one, except Bales 3178 and 3043 whose Kurtosis are greater than one.

It is well known that cotton fibers have large variations even within each variety or bale. Figure 5 illustrates the distribution of fiber width measurement for each of 20 fibers in Bale 3177. It is clear that these twenty fibers varied in their mean ribbon width values and the range of ribbon width values. For instance, the highest mean fiber width (16.55 µm) was observed in fiber 8, while the lowest mean fiber width 11.98 µm was observed in fiber 13. As for the range of fiber width distribution, fiber 15 has the widest fiber width distribution from 7.29 um to 22.40 um; while fiber 12 has the narrowest fiber width distribution from 12.58 um to 16.08 um, which indicates that fiber 12 is more uniform than fiber 15. The coefficient of variation (CV) for the 20 fibers in Bale 3177 is 9.35%. The relatively high variation observed from this study is primarily from the large variation within the cotton bale. One study reported that the coefficient of variation of the mean fiber width from one cotton bale measured by an imaging analysis method was 2.91% (Huang and Xu 2002). The secondary source of error may from our laser measurement system, as indicated by the result from iron wire measurement. It must be mentioned that both the optical system and the pattern processing software will invariably introduce a certain amount of error. For instance, if the laser setup is not assembled such that the laser light illuminates single fibers perpendicularly, this may cause some error in the results obtained. Moreover, if the diffraction patterns obtained were erroneous then the software developed will process erroneous data leading to inaccurate ribbon-width values.

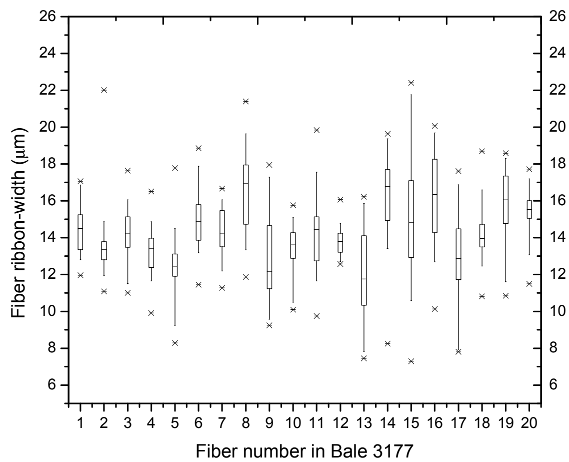

Figure 5. Variation of fiber width measurement within one typical cotton bale.

Conclusion

A laser diffraction optical platform and a software program were developed to measure the fiber ribbon-width of single cotton fibers. The laser diffraction system was validated by testing uniform iron wires and anisotropic cotton fibers. The test on uniform iron wires showed a good accuracy and repeatability of the optical system with 0.1% error and 1.2% coefficient of variation. Tests on cotton fibers demonstrated that the distribution of the cotton fiber ribbon-width of ten bales reflected the difference in fiber fineness and maturity between the bales. This simple, replicable, and relatively inexpensive optical system is capable to scan multiple points along the longitudinal axis of single cotton fibers and reveal the anisotropic nature of cotton fibers. Laser diffraction system described here showed promise to be a new single fiber measurement device for fiber longitudinal profile characterization and cotton fineness and maturity estimation.

Acknowledgement

The authors are grateful for the funding support from Cotton Incorporated. Our gratitude also goes to Dr. E. F. Hequet (Texas Tech University, Lubbock, TX) for providing cotton samples in this study. Special thanks are due to P. Ji from University of Georgia at Tifton for providing access to the microscope which helped during single cotton fiber sample preparation. The authors are also thankful to Timothy Rutland and Gary Burnham, who provided tremendous assistance in preparing the single fibers and collection of diffraction pattern data.

References

Aslan M., J. Yamada, M. P. Mengüç and J. A. Thomasson. 2003. Characterization of Individual Cotton Fibers via Light-Scattering Experiments. *Journal of Thermophysics and Heat Transfer* **17**(4): 442-449.

Hecht, E. 2001. Optics. Reading, Massachusetts, Addison Wesley.

Hequet E. F., B. Wyatt, N. Abid and D. P. Thibodeaux. 2006. Creation of a Set of Reference Material for Cotton Fiber Maturity Measurements. *Textile Research Journal* **76**(7): 576-586.

Huang, Y. and B. Xu. 2002. Image Analysis for Cotton Fibers Part I: Longitudinal Measurements. *Textile Res. J.* **72**(8): 713-720.

Lord, E. 1956. Airflow through Plugs of Textile Fibers. Part II. The Micronaire Test of Cotton. *J. Textile Inst.* **47**(T16-47).

Montalvo, J. G. 2005. Relationships between micronaire, fineness and maturity. Part 1. Fundamentals. *Journal of Cotton Science* **9**(2): 81-88.

Pierce, F. T. and E. Lord. 1939. The Fineness and Maturity of Cotton. *J. Textile Inst.* **30**(T173-210).

Sui R., J. A. Thomasson, Y. Ge and C. Morgan. 2008. Multispectral Sensor for In-Situ Cotton Fiber Quality Measurement. *Transactions of ASABE* **51**(6): 2201-2208.

Tang W., Y. Zhou and J. Zhang. 1999. Improvement on theoretical model for thin-wire and slot measurement by optical diffraction. *Meas. Sci. Technol.* **10**: N119-N123.

Thomasson, J. A., S. Manickavasagam and M. P. Mengüç. 2009. Cotton Fiber Quality Characterization with Light Scattering and Fourier Transform Infrared Techniques. *Applied spectroscopy* **63**(3): 321-330.

USDA AMS. 2001. The classification of cotton. Washington, D.C.: USDA.

Xu, B. and Y. Huang. 2004. Image Analysis for Cotton Fibers Part II: Cross-Sectional Measurements. *Textile Res. J.* **74**(5): 409-416.

Y. Huang and B. Xu. 2002. Image Analysis for Cotton Fibers Part I: Longitudinal Measurements. *Textile Res. J.* **72**(8): 713-720.