SINGLE COTTON FIBER DIAMETER DETERMINATION BY USING FRAUNHOFER DIFFRACTION

Ayodeji Adedoyin
Changying Li
Department of Biological and Agricultural Engineering, University of Georgia
Tifton, GA

Abstract

Knowledge the properties of single cotton fibers may provide for cotton processors and producers a better way to predict and characterize the properties of a bulk sample of cotton. In this work a relatively simple and easily replicable approach is developed to determine the diameter ("ribbon-width") of single cotton fibers and this knowledge may then be used to characterize single cotton fiber quality parameters such as fineness, maturity, and micronaire. The overall objective of this research was to conduct a fundamental study of the optical properties (light diffraction) of individual cotton fibers with the interaction of a monochromatic light beam. The light source used was a 0.8mW linearly polarized He-Ne laser with a nominal wavelength of 633nm. Diffraction patterns generated from the interaction of each cotton fiber and the laser light are captured by using a linear CCD camera. Each fiber was measured at multiple points. The diameter of each fiber was determined from the distance between consecutive fringes of the diffraction patterns generated. Preliminary results show that the average fiber diameters obtained fall within the range of 15-20µm, which is approximately the expected range for a cotton fiber. The shape of the diffraction patterns observed is consistent with the shape of the theoretical solution of light obstructed by a thin wire/fiber. Moreover, the distribution of the diameters follows the tendency of a normal distribution. The approach used in this research may be integrated with existing cotton fiber measurements systems such as HVI and AFIS systems to provide a better characterization of cotton fiber quality.

Introduction

The use of a variety of cotton for a particular application depends on the quality of the cotton. The quality of cotton depends on the cotton fiber properties, namely length, length uniformity, strength, fineness, maturity, trash content, leaf grade, color grade, preparation, and extraneous matter. These properties are used to characterize cotton fiber quality and this characterization can then be used to determine which applications the cotton variety can be used for. Currently, the methods used to characterize the quality of cotton fibers involve analyzing the properties of bulk samples. The properties of single cotton fibers if needed are then extracted from the properties of the bulk samples. Although, analyzing the properties of bulk samples of cotton fibers may provide a cheap and rapid technique to characterize cotton fiber quality, it may not however provide the properties of individual cotton fibers. Fundamentally, knowledge of a single cotton fiber should be used to characterize the properties of a bulk sample of cotton. The micro, not the macro, properties of an entity should be used to characterize the overall properties of an entity, which in this case is cotton fiber quality. Therefore, it is important to develop a universally accepted method that may be used to characterize individual cotton fiber quality and then this characterization can be used to characterize the quality of a bulk sample.

A universally accepted method for characterizing cotton fiber quality is very important to cotton producers and processors. One way to implement such a universal method may be to develop a sensing tool (optical based) that can be used to characterize single cotton fiber quality as proposed by Thomasson et al. (2009). Such an optical approach has been developed in this study. Assuming that cotton producers and processors have the same method of characterizing cotton fiber quality, then producers can prevent the amount of discount they may receive by turning in cotton fibers they know have a high quality and processors will not need a set of multiple devices to determine the quality of a bale of cotton. The classification of cotton fiber quality is done by the United States Department of Agriculture (USDA) by using High Volume Instruments (HVI) systems. HVI systems consist of several devices used to measure different properties of cotton fibers. Moreover, HVI systems measure cotton fiber quality from bulk samples of cotton. Although HVI systems provide a cheap and rapid technique for characterizing cotton fiber quality from bulk samples, they however do not provide a method for characterizing single cotton fiber quality. Furthermore, HVI systems consist of several complex detection devices integrated into one system. In order to better characterize cotton fiber quality, a deeper comprehension of the properties of single cotton fibers is needed and this may not be accurately determined by measuring the properties of bulk samples. Variations in the quality of cotton fibers exist between different portions of a cotton field, from plant to plant, and even within the same plant. Moreover, the quality of fibers on a single seed may vary in length, shape, thickness, and maturity as described in

Jost (2005). It is therefore conceivable that if on a single seed of cotton, there exists variations in the quality of the fibers then a bale of cotton will also contain a highly variable array of fibers. This variation can be attributed to the individual response of each cotton fiber to fluctuations in its growing environment. By studying individual cotton fibers from different parts of a seed, different plants, and different locations on a field, it may be possible to determine the causes of the variation in cotton fiber quality and this is similar to the work done by Cui et al. (2003).

The approach used in this work to study the optical properties of single cotton fiber requires that care be taken during sample preparation. Selecting single cotton fibers is a time-consuming task that requires a high level of concentration and effort. Once the single fibers are extracted from the bulk samples, they need to be carefully secured in place. This is by no means a trivial task if the environmental conditions surrounding the experimental setup are uncontrolled. Single fibers are susceptible to traverse and longitudinal drift in the presence of any air movements and vibrations as observed by Wang and Valdivia-Hernandez (1995). Such drifts can be prevented by using an environment free of vibrations and air movements (air vents, fans, or any other mechanism that may cause air movements). Once the single fibers are secured, the optical properties of the fibers can be determined by illuminating them with a light beam that is perpendicular to the axis of the fiber similar to the approach in Smithgall et al. (1977). In our case, the light source used produces a light beam with a Gaussian intensity profile rather than a beam with uniform intensity. Analytical solutions for the interaction between single fibers and light beams with Gaussian beam profiles are provided by Glass (1998).

The overall objective of this research project was to conduct a fundamental study of the optical properties of individual cotton fibers with the interaction of a laser beam and how this interaction can be related to cotton fiber quality parameters, such as fineness, maturity, and micronaire. More specifically the experimental approach used in this work may be used to develop a simple and inexpensive optical sensing tool to rapidly and accurately measure single cotton fiber quality parameters, investigate the anisotropic nature of the diameter of single cotton fibers by analyzing multiple points along each fiber, and to develop a software program that may be used to automatically characterize the quality of single cotton fibers.

Materials and Methods

The schematic of the experimental setup used in this work to study the optical properties of single cotton fibers is shown Figure 1. The experimental setup, which was assembled in Advanced Fiber Quality Sensing Laboratory (AFQSL), consists of a light source, polarizing lenses (P1), an iris (I1), a single cotton fiber holder (S1), a collecting lens (CL), and a linear CCD camera (CCD). The light source used was a 0.8mW linearly polarized Helium-Neon Laser (HRP008, Thorlabs Inc., Newton, NJ) with a nominal wavelength of 633nm. The diameter of the laser beam immediately emanating from the light source is approximately 0.57mm (570µm) with a beam divergence of 1.41mrad. The light source used has a Gaussian profile, that is, the laser beam has a TEM_{00} mode structure. Two (2) linearly polarizing lenses (LPVISB050, Thorlabs Inc., Newton, NJ) were placed behind the light source to attenuate the intensity of the laser beam. The intensity of the laser light was controlled (reduced significantly) by rotating the transmission axis of the polarizing lenses. This approach of reducing the intensity of the laser beam was used to prevent the line CCD camera from been saturated or damaged. An iris (ID25SS, Thorlabs Inc., Newton, NJ) was placed behind the polarizing lenses and was used to reduce backscattered laser light and any unwanted light interacting with the cotton fiber. The only interaction we are interested in is that between the laser light and the cotton fiber therefore the iris provides a way to prevent any other light sources from interacting with the cotton fibers. A single cotton fiber holder was designed and built to hold each cotton fiber perpendicularly to the transmission axis of the laser beam. To implement a tabletop Fraunhofer diffraction experiment, a collecting lens (LB1676-C, Thorlabs Inc., Newton, NJ) with a focal length of 10cm was placed behind the cotton fiber holder. A linear CCD camera (TCN-1304-U, Mightex Systems, Pleasanton, CA) was used to detect the collected diffraction patterns, which were then saved on a personal computer. The CCD camera captured each diffraction pattern with 3648 pixels at a scanning rate of approximately 150 scans per second. Initial observations showed that the intensity of the center fringe of the diffraction intensity was still high and this may saturate the CCD camera. To prevent saturating the CCD camera, the center portion of the CCD camera was shaded.

The cotton samples used for this study were obtained from the USDA classing office and from the University of Georgia Micro Gin facility. Eight (8) cotton varieties with different micronaire values were obtained and used for this work. Specifically, the cotton fiber varieties are Lint 101 (BCS 614), Lint 108 (ST 5327), Lint 110 (DPL 0924), Lint 203 (PHY 370), Lint 205 (DPL 901), Lint 209 (BCS 0727), USDA 2.6, and USDA 5.47. A total of fifty-six

(56) fibers (seven (7) fibers from each variety) were used for the preliminary results presented in this paper. Over 50 diffraction patterns at different points along the axis of each fiber were measured. By measuring multiple points along each fiber the anisotropy (non-uniformity) of the diameter of cotton fibers can be studied and analyzed.

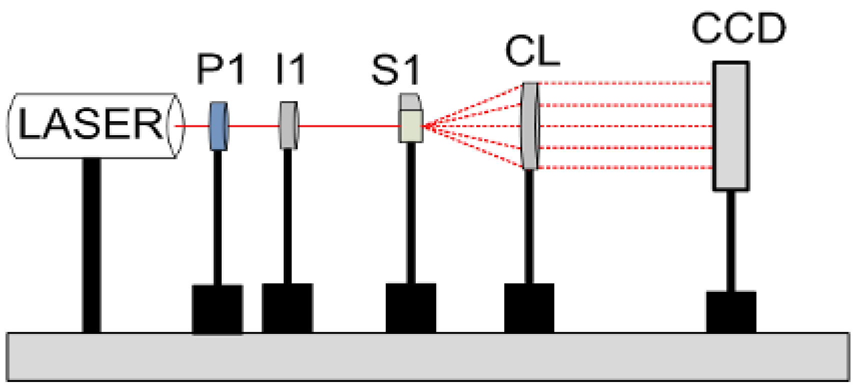

Figure 1. Schematic of experimental setup used to implement tabletop Fraunhofer diffraction.

The diameter of a single cotton fiber can be computed from the diffraction pattern generated by illuminating it with a light source. Figure 2 shows a theoretical diffraction pattern simply to illustrate how the diameter of a fiber can be computed from a diffraction pattern. The normalized intensity (in arbitrary units) is plotted against the length of the observation plane. In order to compute the diameter of a fiber, the dark fringes (low peaks) are identified on either side of the center peak (center fringe). The dark fringes are identified with circular symbols in Figure 2. The distance between consecutive dark fringes are then calculated. Let us denote by D the diameter of a single fiber measured at a single point, then the diameter of the single fiber can be expressed as $D \approx (\lambda f)/(X_2 - X_1)$ where λ is the wavelength of the monochromatic light used, f is the focal length of the collecting lens, and $X_2 - X_1$ represents the distance between consecutive fringes. A similar technique was used to calculate the diameter of wider wires/fibers in Khodier (2004). Ideally the distance between the first and second order fringes should be the same for the distance between the second and third order fringe and this applies for higher order fringes. In some cases we were only able to observe first and second order fringes on either side of the center fringe.

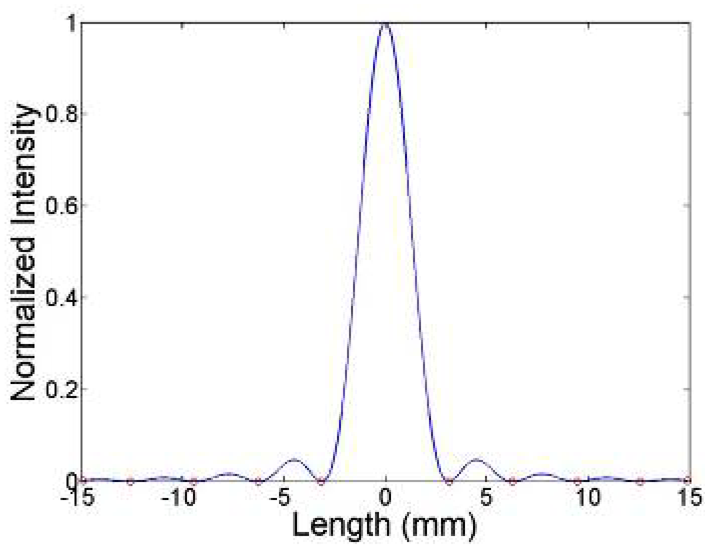

Figure 2. Theoretical solution for diffraction pattern generated by illuminating a single fiber.

Results and Discussion

In Figures 3-6 we present diffraction patterns generated as a result of illuminating with the laser light at single point along the axis of a single cotton fiber. Although the figures show diffraction patterns for the Lint 101, Lint 209, USDA 2.6, and USDA 5.47 varieties, similar patterns were observed for the other four cotton varieties used in this work. Figures 3-6 show the normalized intensity (in arbitrary units) of the diffraction pattern versus the position along the observation plane. In this case the observation plane was a line CCD camera, which was approximately thirty (30) millimeters in length. The symbols in Figures 3-6 represent the experimental data and the solid lines are the denoised signals. The noisy nature of the experimental data obtained presented a challenge (determining the precise location of the high and low peaks) in interpreting the diffraction patterns therefore the experimental signals were denoised by using the one-dimensional single wavelet denoising function provided in MATLAB. As the figures show, the denoised signals agree well with the experimental data.

The selected diffraction patterns presented in Figures 3-6 are in good agreement with the theoretical diffraction pattern (Figure 2), which is usually in the shape of a $\left(\sin^2 x / x^2\right)$ function. As expected, we observed a high peak (center fringe) in the diffraction pattern as well as first and second order fringes on either side of the center fringe. In some cases we were able to observe what may appear to be higher order peaks as shown in Figures 4-6 but further work is needed to verify if indeed these correspond to higher order fringes. It would appear from Figures 3-6 that there are two center fringes in each diffraction pattern but this is not the case. In order to prevent the CCD line camera from being saturated, the portion of the observation plane where the center fringe was incident on the CCD was blocked out. The width of the block out material used was chosen so as to not block out the entire center fringe but leave some portion unblocked to verify that the shape of the diffraction patterns generated agreed with the theoretical solution. This explains the reason why the diffraction patterns appear to have two center fringes.

It was observed that the height of the higher order peaks (fringes) is not uniform from pattern to pattern and this may be due to the nature of the cotton fiber itself. Further analysis of the preliminary results presented in this work will be needed to determine the cause(s) of the change in shape of the diffraction patterns. This change in shape of the diffraction patterns was observed to vary within the same cotton variety as well as between different cotton varieties. Not all diffraction patterns generated at each point along a single cotton fiber generated the same results presented in Figures 3-6. In some cases there were no diffraction patterns noticeable in the observation plane even though the cotton fiber was clearly illuminated by the laser beam. The inability to measure diffraction patterns may be attributed to two main reasons. The width of the CCD line camera was so small that any slight deviation of the diffraction pattern from the detecting portion of the camera will result in diffraction patterns that cannot be observed. Furthermore, from the first point it can be deduced that the angle at which the diffraction pattern is incident on the CCD camera is very important. In order to relax this limitation(s) it may be useful to use a two-dimensional observation plane as opposed to a line observation plane. In this way the deviation of the diffraction pattern will be observed irrespective of the angle of deviation.

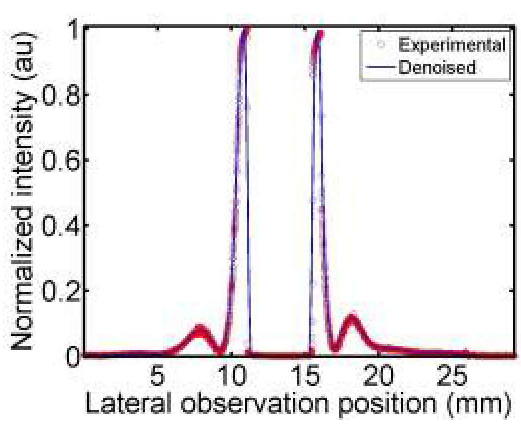

Figure 3. A sample diffraction pattern generated by illuminating a single cotton fiber of variety Lint 101

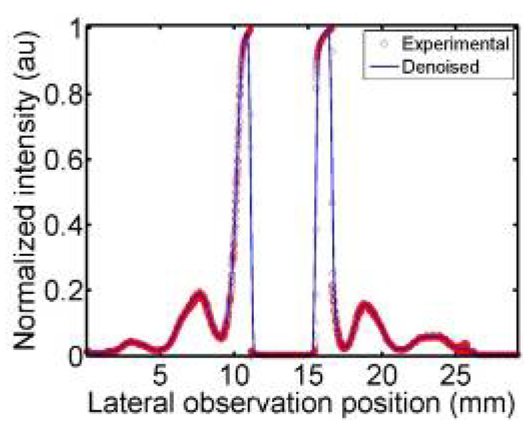

Figure 4. A sample diffraction pattern generated by illuminating a single cotton fiber of variety Lint 209

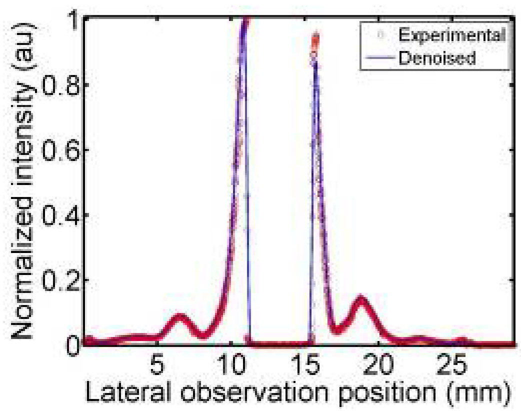

Figure 5. A sample diffraction pattern generated by illuminating a single cotton fiber of variety USDA 2.6

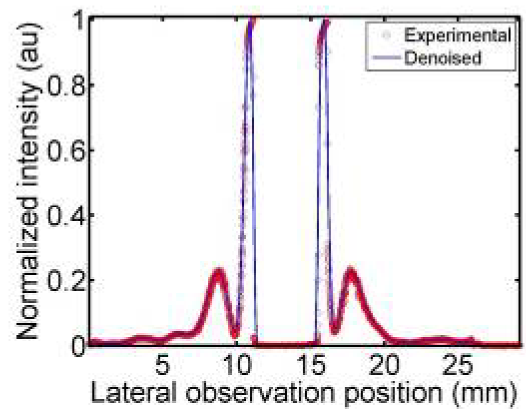

Figure 6. A sample diffraction pattern generated by illuminating a single cotton fiber of variety USDA 5.47

In Table 1 we present the average diameter for each cotton variety obtained by using our laser diffraction technique. In this work it is understood that by fiber diameter we mean the ribbon-width. For each diffraction pattern generated with at least a first order fringe on either side of the center fringe, two diameters were computed. One diameter was computed from the first order fringe on the left hand side of the center fringe and the second from the right hand side. This was done to compare the diameter computations from either side of the center fringe. All the diameter measurements obtained for each cotton variety were then averaged to obtain the average diameters presented in Table 1. These preliminary results seem encouraging because the average diameters fall within the expected range for cotton fibers in general, that is, between 15-20µm. For more accurate results, more fibers will need to be tested to form a better representation of the particular variety. The average diameters obtained for each variety are too close to each other to be used to differentiate between the cotton varieties but all the varieties used for this study have different micronaire values. If we can relate the measured diameter of each fiber to the micronaire values, then we may be able to differentiate each variety by using our optical method.

Table 1. Average diameter computed from the resulting diffraction pattern of each cotton variety.

Cotton Variety	Average Diameter (µm)
LINT 101	16.517
LINT 108	15.521
LINT 110	15.354
LINT 203	15.609
LINT 205	17.182
LINT 209	16.578
USDA 2.6	15.195
USDA 5.47	15.072

A single cotton fiber or a sample of cotton fibers observed under a microscope reveals that the diameter of a cotton fiber is not uniform along the fiber axis. The optical approach developed in this work can also be used to study the anisotropic nature of the diameter of cotton fibers. By illuminating multiple points and studying the resulting diffraction patterns at each point along a fiber we are able to determine the diameter of a single fiber at various points. In this way we are able to analyze the presence of convolutions in single cotton fibers. A distribution of average diameters measured for the Lint 108 cotton variety is presented in Figure 7. The expected results from such a study would suggest that the shape of such a distribution should show a normal (Gaussian) distribution. This may be the case if more fibers and more points are measured. Nonetheless, encouraging results can be seen from Figure 7. The figure shows that most of the points measured were about the average (15 µm). The values of the diameters seem to fall off on either side of this average value. Although not the expected normal distribution, the trend seen in the figure suggests the same trend as that of a normal distribution. A very similar trend may be deduced from Figure 7 but further work is needed to make such a concrete generalization.

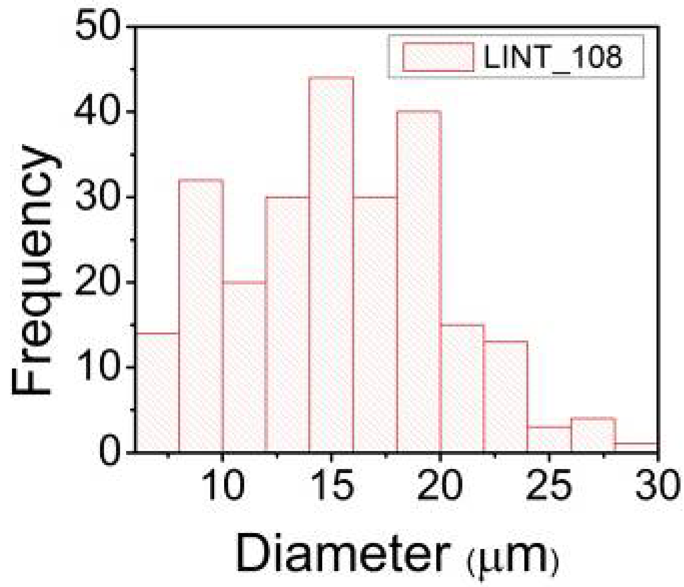

Figure 7. Distribution of cotton fiber diameters for the Lint 108 variety.

The single cotton fiber diameter results obtained and presented in this section represent the "ribbon width" of each fiber. To verify the accuracy of this methodology the results obtained via our Fraunhofer method will need to be compared with cross-sectional diameter of each single fiber from each cotton variety. The cross-sectional diameter of each fiber may provide a more accurate representation of the fiber's diameter than the ribbon width. Obtaining the cross-sectional diameter of a cotton fiber is a little bit more challenging than the method used in this work. If a correlation can be made between the cross-sectional diameter and the "ribbon width" we compute the method used in this work can be validated.

Conclusion

The optical properties of single cotton fibers was studied and analyzed by illuminating single cotton fibers with a monochromatic laser light. The diffraction pattern generated as a result of the interaction between the laser light and each single cotton fiber was analyzed and presented. A relatively simple methodology was used to measure the average diameter (ribbon-width) for each cotton variety used in this work. Diffraction patterns generated are in good agreement with the theoretical solution even though the theoretical solutions are for fibers illuminated by uniform light and not Gaussian light beams as the approach used in this study. Numerical algorithms and techniques have been developed to detect the dark fringes within each diffraction pattern and to compute the average diameter of a single point along the fiber axis. Diameter measurements obtained fall within the expected range (15~20 μm) for the diameter of a cotton fiber.

More work is needed to determine the quality parameters of the single cotton fibers. Since the micronaire values for each cotton variety used are known then in order to validate the methodology an algorithm to compute micronaire values is paramount in the next stage of this work. The distribution of diameters for each cotton variety follows the trend of a normal distribution and more samples will be tested to provide a more accurate generalization of a cotton variety. Obtaining consistent diffraction patterns for every point along a fiber may be accomplished by using a two-dimensional observation plane instead of a line CCD camera which may not be able to detect diffraction patterns that are not along the same axis.

It can be deduced from the preliminary results that the current methodology is capable of determining the diameter of single cotton fibers. A correlation between the measured diameter and cotton fiber quality parameters, specifically fineness, maturity, and micronaire will be developed to validate the accuracy of our technique. The diameter of single cotton fibers was verified to be anisotropic in nature confirming the presence of convolutions along the axis of the single fibers. Research currently underway will continue to optimize numerical techniques developed and to develop numerical models to determine the fineness, maturity, and micronaire values by illuminating single cotton fibers with a laser light.

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