Contents copyright ©2006 by SAGE publications All right reserved

Apart from fair dealing for the purposes of research or private study, or criticism or review, and only as permitted under the Copyright Designs and Patents Act, 1988, this publication may only be reproduced, stored or transmitted in any form or by means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction, in accordance with the terms of licenses issued by the Copyright Licensing Agency. Inquiries concerning reproduction outside those terms should be sent to the publishers.

SAGE Publications is a member of CrossRef

The final, definitive version of this paper has been published in Textile Research Journal, 76/5, May/2006 by <<SAGE Publications Ltd.>>/<<SAGE Publications, Inc.>>, All rights reserved. © Copyright 2005.

This article is also available online at:

<http://trj.sagepub.com/cgi/reprint/76/5/426>

Fiber Length Distribution in Cotton Processing: Dominant Features and Interaction Effects

Abstract This study investigated the unique shape of cotton fiber length distribution and explored its main features. One prominent feature revealed by the examination of a multitude of distributions measured on a wide range of cotton samples was the modality of the distribution pattern. Based on the experimental data, significant interactions were identified and highlighted between the distribution modality (quantitatively described as a measure of departure from unimodality), some fundamental properties of cotton fiber including maturity and strength, and the extent/aggressiveness of the mechanical processes undergone by the cottons.

Key words cotton fiber properties, staple length distribution, distribution shape, fiber damage, bimodal distribution, DIP statistic

Mourad Krifa¹

*International Textile Center, Texas Tech University,
Lubbock, Texas 79409, USA*

Among all measured characteristics of cotton fiber, length has always been considered to be the most crucial. The end-use of the fiber and the processes adopted for its transformation are largely determined by its length properties.

Notwithstanding the early statements to the effect that adequately describing the length of a fiber sample is only possible by considering the entire distribution [1, 2], the cotton industry has focused primarily on measuring the length of the longest fibers in a cotton sample. This long-established practice derived from the early methods of manual classing based on the concept of staple length, and was carried over by the evolution and modernization of length measurement instruments (span lengths, upper half mean length, upper quartile length...). For decades, these parameters have accommodated the measurement needs of the cotton industry. In recent years, however, the problem of short fibers has come to the forefront of concerns for the global cotton industry. Indeed, with the evolution toward high-speed production technologies, the mechanical treatments undergone by the fiber became more and more aggressive. This, along with more stringent requirements imposed on raw cotton quality, has increasingly shifted interest towards the short fibers.

The adverse effects of short fibers have become the subject of a unanimous consensus among all sectors of the cotton industry, which made the objective of minimizing short fibers a top priority in cotton research. In the research reported to date, a variety of length measurement methods were used to quantify short fibers. Various parameters were defined for this purpose. Tallant et al. [2, 3] defined the short fiber content as the percentage of fibers 9.53 mm (0.375 inch) and shorter. Lord [1] used the percentage of fibers shorter than half the "effective length" as a definition. Lord also introduced the percentage of fibers shorter than a fixed length as a possible useful definition for some particular purposes. Eventually, all definitions evolved into a single measure arbitrarily defined as the percentage of fibers shorter than 12.7 mm (0.5 inch), and designated as the "short fiber content" or SFC.

Early instruments to measure fiber length distribution were based on the comb sorter, or staple diagram, formed by manually arranging the fibers in ordered length groups. The Sutter-Webb array is one of these methods and is usually used as a reference for length distribution measure-

¹ E-mail: Mourad.krifa@ttu.edu

ment [4], although it is widely acknowledged that its reliability is limited due to its tediousness and dependence on operative skill and experience [5].

High volume instrument (HVI) length measurement provides the “fibrogram”, or the second integral of the length frequency histogram [6–8]. It is used to derive three main parameters: the mean length (ML), the upper half mean length (UHML; average length of the 50% longest fibers by weight, used for staple classification), and the uniformity index (ratio of ML to UHML expressed in %). Note that among all the parameters made available by the existing range of instruments and methods, the uniformity index (or the uniformity ratio) represents the only commonly used shape parameter of the length distribution [8].

Attempts have been made to estimate short fibers from the HVI using different techniques. The simplest consist of establishing regression equations between HVI length parameters and the SFC [9–11]. Other approaches are based on deriving the entire length frequency histogram from the fibrogram [9, 12–14].

Another major instrument used by the cotton industry to measure fiber length distribution is the Advanced Fiber Information System (AFIS®) from Uster Technologies [15–18]. It measures properties of single fibers individualized by an aeromechanical device and conveyed by airflow to a set of optical sensors, where they are counted and characterized. Among other fiber properties (fineness, maturity, neps and trash particles), the AFIS provides a variety of length parameters: mean length by number (L_n), and by weight (L_w), upper quartile length by weight (UQL_w), length CV% by weight and by number, short fiber content by weight ($SFC_w\%$) and by number ($SFC_n\%$), and length upper percentiles by number ($L_{n2.5\%}$ and $L_{n5\%}$). It must be emphasized that the length distribution by number constitutes the source of all these parameters. The weight-biased distribution (and parameters) is estimated from the

latter based on the assumption of a uniform fineness across all length categories. (Strictly speaking, the distribution “by weight” is in fact a length-biased distribution.)

The use of the AFIS for length distribution measurement has become more and more prevalent as a result of the increased concern regarding short fibers. The prominence of the short fiber issue has eventually refocused the interest on the notion of length distribution, as recommended by Lord [1] and others over many decades, and attempts have been repeatedly made to provide length data that is representative of the entire distribution. The AFIS has the functionality necessary to generate a complete histogram of the length distribution of cotton samples; however, this is seldom if ever done in commercial applications. Effective utilization of length histogram data requires an understanding of the unique shape of the cotton fiber length distribution and the difficulties inherent to its parameterization. This paper examines some of the issues related to the shape of cotton fiber length distribution, its main features and its determining factors.

Material and Methods

A range of 67 commercial cotton bales grown in three US production areas over two crop seasons (2002, 2003) were selected. Each bale was sampled at 10 layers throughout, with fiber measurements being done on each layer. The main HVI fiber properties of the selected bales are summarized in Table 1 (four replications for Micronaire, four for color, and 10 for length and strength).

In addition to HVI analysis, all samples were tested on AFIS® (three replications of 3000 fibers each) and length histogram data were retrieved, along with the usual parameters. The latter are also summarized in Table 1.

Table 1 Main fiber properties of the selected bales (HVI and AFIS measurements on bale samples).

Fiber properties	Min.	Max.	Average
HVI			
Micronaire	2.3	5.1	4.2
Upper half mean length (UHML, mm)	24.9	30.8	27.6
Length uniformity (%)	79.0	84.1	81.6
Strength (g/tex)	22.3	33.9	29.3
Elongation (%)	3.7	9.5	6.7
AFIS			
Mean length by number (L_n , mm)	15.1	22.0	19.1
Short fiber content by number (SFC_n , %)	18.2	41.4	26.8
Mean length by weight (L_w , mm)	19.8	26.8	23.8
Short fiber content by weight (SFC_w , %)	5.5	15.4	9.5
Upper quartile length by weight (UQL_w , mm)	25.0	32.1	28.8
Maturity ratio (MR)	0.76	0.95	0.89
Fineness (mtex)	151	190	172

Finally, on a subset of the bales, additional length distribution data were obtained from fiber samples collected after an aggressive opening action performed by a fiber individualizer of the type used in open-end rotor spinning.

We examined all this data to evaluate the characteristic shape of cotton fiber length distribution and its main features. The relationships and interactions between these features (distributional shape) and the structural properties of cotton fibers (maturity, fineness, strength...) were then explored. Finally, issues relating to the alteration of the length distribution pattern when the fiber was subjected to mechanical processing were considered.

As previously mentioned, given the nature of the AFIS® test (single fibers), the numerical length distribution (by number) constitutes the source from which all length parameters are derived (both by number and by weight). The following discussion is based on numerical length distribution data. Issues relating to the length-biased distribution (by weight) will be treated at a later stage of the research.

Results and Discussion

Length Distribution Pattern

The examination of AFIS results obtained on the 67 cotton bales revealed some typical features of the length distribution patterns. Figure 1 depicts the results for two groups of four cottons each, exemplifying the varied length distribution patterns encountered (with similar staple lengths within groups: 24.9 to 25.4 mm and 27.9 to 28.4 mm, respectively).

Despite the different patterns, all cottons presented a local peak in the range of very short fibers (3.2 mm or 0.125 inch). The precise origin of this fiber fragment accumulation is, at this point, unclear. However, it is likely to be related to fiber breakage occurring during the mechanical processing of the fiber, or during the testing procedure itself. Indeed, it is necessary to bear in mind the aggressive opening action exerted by the AFIS in order to individualize the fibers.

A similar peak was noticed by Schneider et al. [19] using a measurement method based on image analysis, and was attributed to fiber breakage during ginning. Schenek et al.

Figure 1 Length distribution pattern: Group 1: UHML = 24.9-25.4 mm (staple 31-32); group 2: UHML = 27.9-28.4 mm (staple 35-36).

[17] used a manual method for single fiber length measurement [20] and noticed a close agreement with the AFIS distribution in the range of short fibers. This suggests that the accumulation of fiber fragments predominantly occurred in the course of fiber mechanical handling (ginning, lint cleaning), rather than during the AFIS opening.

In addition to the fiber fragment peak (3.2 mm), four of the distributions (patterns (c) and (d) in each of the graphs of Figure 1) show a second distinct mode towards the longer fibers with a dip between the two peaks. The length distribution labeled (a), on the other hand, presents an almost flat plateau with the only discernible peak located at 3.2 mm.

Examination of the main fiber properties of the bales that were tested revealed that the distribution patterns shown above were associated with different levels of fiber maturity and strength. To illustrate this dependence, fiber maturity was used as a selection criterion and constituted two sets of cottons, with differing maturity levels, were constituted. Fiber bundle strength levels measured by HVI were, of course, different between the two sets, given the inherent relationships among the complex maturity-fineness and strength.

The first set of samples was characterized by a maturity ratio of 0.79 and less (immature, weak fibers), whereas the second set was made up of cottons having a maturity ratio exceeding 0.9 (mature, strong fibers). The length distributions of the two sets of samples are shown in Figure 2.

The similarities in the distribution patterns within each set (i.e., each maturity and strength level) are obvious. The immature weak cottons show length distributions similar to the pattern designated (a), whereas the mature strong cottons exhibit a distribution comparable to the pattern labeled (d) (compare with Figure 1).

These observations strongly suggest a significant influence of maturity and strength on the shape of fiber length distribution. The most apparent distribution feature affected by these properties is the existence or non-existence of two distinct modes. Based on the results illustrated in Figure 2, immature and weak cottons exhibit a unimodal distribution whereas mature and strong ones tend to show a bimodal length distribution.

As stated above, these observations are based on visual inspection of the length distribution shapes of two sets of selected cottons with significantly different maturity and

Figure 2 Observed length distribution for immature-weak and mature-strong fibers.

strength values (extreme cases). In order to generalize the conclusions and allow inclusion of a wider range of cotton samples (including intermediate cases, i.e., with average maturity and strength), a parametric description of length distribution is required.

Modality of the Length Distribution

As a first approach, the focus was placed on describing of the modality of the distributions was obtained, since this feature represented the most visually striking difference between length distributions of immature-weak cottons (unimodal pattern) and mature-strong ones (bimodal pattern). To explore these characteristics objectively, a formal statistical tool was sought to quantitatively measure the strength of bimodality and determine its statistical significance (or, in more general terms, measure multimodality; that is, to quantify evidence against unimodality).

There are several methods reported in the literature that help test the modality and determine the number of

modes in an empirical distribution [21–25]. Hartigan's DIP test for unimodality [23, 24] was used for two main reasons. First, the test is based on calculation of the DIP statistic, which quantitatively measures departure from unimodality. This would provide a quantitative criterion that can be used to discriminate between the distributional shapes within the range of cottons. Second, the DIP test is distribution-free; i.e., it does not require a priori assumptions on the nature of the distribution being observed.

Hartigan and Hartigan [23] define the DIP statistic as “the maximum difference, over all sample points, between the empirical distribution function, and the unimodal distribution that minimizes that maximum difference” (i.e., the maximum difference between the empirical CDF and the unimodal CDF closest to it, with CDF: cumulative distribution function). Derivation of the DIP statistic is based on the fundamental definition of a unimodal distribution function, which stipulates that a distribution function $F(x)$ is unimodal with mode m if $F(x)$ is convex in the interval $(-\infty, m]$ and concave in $[m, \infty)$ [23, 26]; $F(x)$ being the cumulative distribution function or CDF. The unimodal

Figure 3 Illustration of the modality test. (a) Immature-weak cotton; (b) Mature-strong cotton.

CDF closest to the empirical distribution F , given the mode m_0 is, by virtue of the definition above, the greatest convex minorant of F on $(-\infty, m_0]$ and the least concave majorant on $[m_0, \infty)$ [23, 24, 27]. (The greatest convex minorant of F on $(-\infty, m_0]$ is defined as "the convex function G not exceeding F on $(-\infty, m_0]$ that minimizes $\sup_{x \leq m_0} |F(x) - G(x)|$ ". The least concave majorant is defined analogously [23, 27].)

Further description of the principles underlying the computation of the DIP statistic can be found in the open literature [23, 24, 27]. The original FORTRAN routine written by Hartigan to compute the DIP statistic can be found in reference [24]; an updated version of the FORTRAN routine can be found in [28]. A translation of the latter into Matlab was used to do the computations in the present study.

Figure 3 shows two length distribution histograms, as generated by AFIS[®], with an illustration of the DIP statistic concept. Note that, as specified above, the DIP statistic is computed based on CDF fits and cannot be quantified from PDF representations. However, the latter is used in Figure 3 due to its visual impact, which seemed more appropriate for illustrating the modality concept in the present case.

The upper graph in Figure 3 (case a) represents the empirical length histogram of an immature-weak cotton, along with the plot of the unimodal PDF closest to it, derived based on Hartigan's procedure (broken line). In this first case (immature-weak cotton), the DIP statistic is estimated at 0.0027 and the unimodal fit appears rather close to the empirical histogram.

The bottom graph in Figure 3 (case b) shows an analogous representation of the length distribution of a mature, strong cotton. The discrepancy between the unimodal fit and the empirical data appears greater than in the previous case. The DIP statistic adequately reflects this discrepancy

and its value is 4.5-times higher than for the immature-weak cotton (0.0122 compared to 0.0027).

The concepts illustrated above were applied to all the length distribution data collected from AFIS[®] analysis. Using the raw fiber data (ten layers per bale), the DIP statistic was estimated for each individual layer in order to examine the variation of the distribution modality within bales of cotton (between layers), in addition to the variation among different cottons. The results are summarized in the box plots of Figure 4 (67 juxtaposed plots, one box plot represents one cotton bale).

The box plots of Figure 4 show DIP statistic values that appear rather dispersed within some of the tested bales (with a varying degree of scatter from one bale to another, and some apparent outliers; the outliers are defined as those observed values higher than the upper quartile plus $1.5 \times \text{IQR}$ and lower than the lower quartile $-1.5 \times \text{IQR}$, with IQR being the inter-quartile range [29]). The number of observations made on each bale (10 layers) was not sufficient for a thorough analysis of the within-bale distribution of the DIP statistic and of the incidence of outliers. On the other hand, the results were ample to show a highly significant between-bale variability of the distribution modality measure, as evidenced by both the parametric one-way ANOVA and the non-parametric Kruskal-Wallis test, which yielded low probability values associated with the between-groups (bale-to-bale) comparison ($p < 0.001$, see Figure 4).

As previously stated, observations made on selected cottons (Figures 2 and 3) suggested a close relationship between the length distribution modality (or, more generally, shape) and some fundamental structural properties of the cotton (maturity-fineness, strength). Using the quantitative measure of the distribution modality (DIP statistic), it is now possible to examine these relationships over the entire set of cottons that were tested.

Figure 4 Box plots of the DIP statistic computed from individual layer data for the 67 cotton bales.

Table 2 contains simple correlation coefficients obtained between the calculated length distribution modality parameter and the fiber properties mentioned above (based on the average values of the 10 layers). With the exception of fiber fineness, the correlation coefficients

Table 2 Correlation between fiber properties and length distribution modality (DIP statistic).

Fiber property	Correlation coefficient	Prob.
HVI		
Micronaire	0.48	< 0.001
Strength (g/tex)	0.76	< 0.001
AFIS		
Maturity ratio (MR)	0.52	< 0.001
Fineness (mtex)	0.15	0.237

were highly significant for all parameters (namely Micronaire, fiber strength, and maturity ratio). Strength, Micronaire and maturity ratio exhibited positive correlation coefficients, indicating that the stronger and more mature cottons had length distributions that departed more appreciably from unimodality. The strongest correlation was with fiber strength.

Scatter plots relating the length distribution modality to fiber strength and maturity ratio are shown in Figures 5 and 6, respectively. As suggested by the correlation coefficients of Table 2, the data points are more dispersed when considering the relationship involving maturity (Figure 6). Nevertheless, both plots exhibit a marked curvilinear trend and display a larger scatter towards high strength and high maturity levels. This pattern suggests that low strength and maturity levels invariably result in a fiber length distribution that is virtually unimodal (low DIP values, with little variation from one cotton sample to another). High strength and maturity levels, on the other hand, show glo-

Figure 5 Relationship between length distribution modality (DIP) and fiber strength.

Figure 6 Relationship between length distribution modality (DIP) and maturity ratio.

bally higher DIP statistic values that varied over a considerably wider range.

The increased variability that accompanied higher maturity and strength levels might be due to interaction effects of other fiber properties (e.g., fineness), as well as to differences in mechanical or other damage done to the fibers. Based on the patterns of Figures 5 and 6, it appears conceivable that immature-weak cottons will show a unimodal length distribution (low DIP value) almost independently from the aggressiveness of the upstream processes to which they were subjected (the fibers will break even under relatively gentle conditions). The length distribution modality of mature-strong cottons, on the other hand, will show a greater dependence on the aggressiveness of the processes (and possibly other fiber properties), which explains the greater scatter observed on Figures 5 and 6 (along with the higher DIP values) for high strength and maturity levels.

To further explore this issue, the following paragraph is dedicated to examining the changes in fiber length distribution pattern, and particularly its modality, when the cottons were subjected to aggressive opening operations.

Length Distribution Alteration during Processing

A unimodal distribution (with a low DIP value) signals extensive breakage of cotton fibers. This pattern is characteristic of an immature-weak cotton, but could also be observed for a mature-strong cotton that has an aggressive processing history (i.e., was subjected to excessive damage). Figures 7 and 8 illustrate the change of the length distribution patterns of two selected cottons that had been processed through an aggressive opening action (fiber individualizer, see Methods section).

Figure 7 Length distribution pattern alteration after aggressive mechanical opening – Case 1: mature-strong cotton (with a bimodal initial length distribution).

Figure 8 Length distribution pattern alteration after aggressive mechanical opening – Case 2: immature-weak cotton (with a unimodal initial length distribution).

One can rightly infer from the bimodal shape of the initial distribution (raw fiber) that the cotton depicted in Figure 7 was a relatively mature and strong one. The data shown in Figure 8, on the other hand, corresponds to a cotton with lower strength and maturity levels, and its length distribution (raw fiber) shows no evidence of bimodality.

After undergoing the aggressive mechanical action of the fiber opener-individualizer, neither of the two cottons showed evidence of bimodality. The initially bimodal distribution of the mature-strong cotton (Figure 7) shifted toward shorter lengths and took a shape that resembled, rather strikingly, those observed in Figure 1 (pattern (a)) and Figure 2 (immature-weak cottons).

As for the immature-weak cotton (Figure 8), its distribution appeared to be squeezed towards the left end of the length axis; i.e., it became dominated by short fibers. Obviously, there was no change in the modality in this second case, the raw fiber length distribution being already unimodal.

These results highlight the close relationship between the length distribution modality and the mechanical damage incurred by the fiber. Particularly, a unimodal distribution observed at the raw-fiber stage is a clear indication of excessive fiber damage due either to fiber immaturity and weakness or to poor conditions in upstream processes (excessive aggressiveness).

Summary Discussion

The present results showed that the shape of fiber length distribution was dependent both on the processing history of the cotton and on those fiber properties that determine the behavior of the cotton during these processing phases (i.e., its propensity to break). The modality feature (existence of one single, or two distinct modes in the distribution) seems to be representative of this dependence. Cottons with low propensity to break have bimodal length distributions that evolve toward unimodality under further mechanical damage. Cottons with a high propensity to break (immature-weak) have length distribution patterns with no evidence of bimodality even in the early stages of the cotton process. At these stages, a measure of the distribution modality could provide valuable clues that are relevant to the processing history of any given cotton, as well as to the length alteration behavior to be expected in further processing. Such a measure could represent a diagnostic tool for optimizing the handling and utilization of the cotton fibers.

Several aspects related to this research remain to be investigated. For instance, processes preceding the compressed bale, ginning in particular, are currently being investigated in order to determine where in the cotton chain the bimodal structure of the distribution first appears. Clues available to date seem to point to the gin stand as the genesis of this bimodal structure. However,

conclusive research with a special focus on the distribution modality and its evolution at the gin is yet to be completed. Objectives pursued in the author's current research also include identifying the main factors (varietal, environmental, process-related...) that affect the cottons' propensity to break. Furthermore, other features of the fiber length distribution are still being explored, with the primary objective of fully parameterizing its pattern and describing its interactions with the processing performance of cotton. Results related to these aspects will be described in future publications.

Conclusions

Using a broad range of 67 cotton bales, the fiber length distribution pattern was examined and the interactions involving its features were explored. The results revealed important interactions relating the shape of fiber length distribution to strength and maturity properties and to mechanical processing of the cottons. The shape of the length distribution depends on both: (1) the resistance to breakage (or propensity to break) inherent to the fiber; and (2) the aggressiveness of the mechanical processes to which the cotton is subjected. One prominent distributional feature revealed in the analysis is the modality of the distribution (or departure from unimodality). Evidence of bimodality observed in length distributions of bale samples (raw cotton) appeared to correlate with high resistance to breakage (higher strength and more mature fibers). Subjecting the raw fiber to mechanical stresses (opening, cleaning...) appeared, through a process of breakage, to gradually dissipate the bimodal structure of the distribution, which shifted towards shorter lengths. Eventually, after sufficient mechanical damage has been administered to the fibers, the bimodal character of the distribution evolved into a unimodal one.

Some samples showed no evidence of bimodality in the bale. These correspond to cottons with low maturity and strength values; i.e., having a higher propensity to break. The unimodal structure can also result from excessive mechanical treatment of the fiber during harvesting, ginning, and lint cleaning.

One relevant question raised by these results, is where in the cotton chain does the bimodal structure of the length distribution first appear? Data collected up to now, along with clues available from the literature, indicate that it may start at the gin stand. However, further analysis of the type presented herein is to be performed on fiber samples collected in the upstream processes (preceding the spinning mill) in order to answer this question. Another issue to be considered is that despite the relevant information revealed by consideration of the distribution modality, other features of the cotton fiber length distribution

remain to explore. These are the focus of the author's current research, as efforts continue to fully describe and eventually parameterize the length distribution pattern. These results will be reported in future publications.

Acknowledgement

The Texas Food and Fibers Commission supported this research.

Literature Cited

1. Lord, E., "The Characteristics of Raw Cotton", Manual of Cotton Spinning, A. F. W. Coulson and M. Tordoff, Eds. Vol. 2, Part 1, The Textile Institute and Butterworth & Co., Manchester, UK, xii + 333 pp. 1961.
2. Tallant, J. D., Fiori, L. A., and Legendre, D. C., The Effect of Short Fibers in a Cotton on its Processing Efficiency and Product Quality. Part I: Affecting the Short Fiber Content by the Addition of Cut Cotton Fibers., *Textile Res. J.* **29**(9), 687–695 (1959).
3. Tallant, J. D., Fiori, L. A., and Landstreet, C. B., The Effect of Short Fibers in a Cotton on its Processing Efficiency and Product Quality. Part II: Yarns Made by Miniature Spinning Techniques from Differentially Ginned Cotton, *Textile Res. J.* **30**(10) 792–795 (1960).
4. ASTM, Standard Test Method for Fiber Length and Length Distribution of Cotton Fibers (Array Method) - D1440-90, in "Annual Book of ASTM Standards," Vol. 07.01, American Society for Testing and Materials: Philadelphia, PA, USA, 1994.
5. Hill, D. W., Instrumentation in Process and Product Control in the Textile Industry, *J. Sci. Instrum.* **42**(8), 557–562 (1965).
6. Hertel, K. L., A Method of Fiber-Length Analysis Using the Fibrograph, *Textile Res.* **10**(12), 510–525 (1940).
7. Prier, H. W. and Sasser, P. E., The Mathematical Basis of Fiber-Length Analysis from Fibrogram Data, *Textile Res. J.* **42**(7), 410–419 (1972).
8. Zeidman, M. I., Batra, S. K., and Sasser, P. E., Determining Short Fiber Content (SFC) in Cotton. Part 1. Some Theoretical Considerations, *Textile Res. J.* **61**(1), 21–30 (1991).
9. Barger, J. D., and Sasser, P. E., Cotton Short Fiber from Fibrogram and Regression Analysis, in Proc. "Beltwide Cotton Conferences – Cotton Quality Measurements". New Orleans, LA., January 10–14, 1993, National Cotton Council of America, TN, USA, pp. 1142–1145.
10. Bragg, C. K., Barger, J. D., and Griffith, S. R., Use of Mean Length as an Indicator of Short Fiber Content, in Proc. "Beltwide Cotton Conferences – Cotton Quality Measurements". New Orleans, LA., January 10–14, 1993, National Cotton Council of America, TN, USA, pp. 1150–1153.
11. Zeidman, M. I., and Batra, S. K., Determining Short Fiber Content (SFC) in Cotton. Part 2. Measures of SFC from HVI Data - Statistical Models. *Textile Res. J.* **61**(2), 106–113 (1991).
12. Krowicki, R. S., Thibodeaux, D. P., and Duckett, K. E., Generating Fiber Length Distribution from the Fibrogram, *Textile Res. J.* **66**(5), 306–310 (1996).
13. Riley, C. R., and Galyon, M. E., Update on Short Fiber Measurements, in Proc. "Beltwide Cotton Conferences – Cotton Quality Measurements". New Orleans, LA., January 10–14, 1993, National Cotton Council of America, TN, USA, pp. 1146–1149.
14. Riley, C. R., and Chu, Y.-T., Short Fiber Measurement from HVI, in Proc. "Beltwide Cotton Conferences – Cotton Quality Measurements". San Diego, CA, January 5–8, 1994, National Cotton Council of America, TN, USA, pp. 1389–1392.
15. Bragg, C. K., and Shofner, F. M., A Rapid, Direct Measurement of Short Fiber Content, *Textile Res. J.* **63**(3): 171–176 (1993).
16. Jones, P. C., Khan, M. A., Galyon, M. E., and Qaud, M., Measurement of Short Fiber Content using AFIS Length and Diameter, in Proc. "Beltwide Cotton Conferences – Cotton Quality Measurements". San Diego, CA, January 5–8, 1994, National Cotton Council of America, TN, USA, pp. 1641–1644.
17. Schenek, A., Knittel, S., Quad, M., and Schleth, A., Short Fiber Content Determination by Means of AFIS, in Proc. "International Committee on Cotton Testing Methods – Meeting of the ITMF Working Group on Fiber Length". Bremen, Germany, March 10–11, 1998, International Textile Manufacturers Federation, Zurich, Switzerland, pp. 161–166.
18. Schleth, A., Status Report on AFIS Short Fiber Content Measurement, in Proc. "International Committee on Cotton Testing Methods – Meeting of the ITMF Working Group on Fiber Length". Bremen, Germany, February 29–March 1, 2000, International Textile Manufacturers Federation, Zurich, Switzerland, pp. 27–41.
19. Schneider, T., Rettig, D., and Mussig, J., Single Fiber Based Determination of Short Fiber Content, in Proc. "Beltwide Cotton Conferences – Cotton Quality Measurements". San Diego, CA, January 5–8, 1994, National Cotton Council of America, TN, USA, pp. 1511–1513.
20. DIN-53808-1, "Testing of Textiles – Determination of Length of Fibers by Measuring of Individual Fibers." Deutsches Institut für Normung e. V.: Berlin, Germany, 2003.
21. Bhattacharya, C. G., A Simple Method of Resolution of a Distribution into Gaussian Components, *Biometrics* **23**(1), 115–135 (1967).
22. Doehlert, D. C., McMullen, M. S., Jannink, J.-L., Panigrahi, S., Huanzhong, G., and Riveland, N. R., Evaluation of Oat Kernel Size Uniformity, *Crop Sci.* **44**(4), 1178 (2004).
23. Hartigan, J. A., and Hartigan, P. M., The Dip Test of Unimodality, *Ann. Statist.* **13**(1), 70–84 (1985).
24. Hartigan, P. M., Computation of the Dip Statistic to Test for Unimodality, *Appl. Stat.* **34**(3), 320–325 (1985).
25. Zhang, C., Mapes, B. E., and Soden, B. J., Bimodality in tropical water vapour, *Q. J. R. Meteorol. Soc.* **129**(594), 2847–2866 (2003).
26. Medgyessy, P., "Decomposition of Superpositions of Density Functions and Discrete Distributions." John Wiley & Sons, New York, 308 pp. 1977.
27. Tantrum, J., Murua, A., and Stuetzle, W., Assessment and Pruning of Hierarchical Model Based Clustering, in Proc. "9th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining", Washington, DC, August 24–27, Association for Computing Machinery, New York, USA, pp. 197–205, 2003.
28. Mechler, F. Computation of the Dip Statistic to Test for Unimodality (Modification by F. Mechler, Sep 2002). Algorithm AS 217, *Appl. Statist.* **34**(3), (<http://lib.stat.cmu.edu/apstat/217>).
29. Chambers, J. M., Cleveland, W. S., Kleiner, B., and Tukey, P. A., "Graphical Methods for Data Analysis", Wadsworth International Group – Duxbury Press, Belmont, CA. 395 pp. 1983.