Optical Spun Yarn Diameter: On-Line Control and Analysis of Count

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OPTICAL SPUN YARN DIAMETER: ON-LINE CONTROL AND ANALYSIS OF COUNT

By

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I dedicate this study to my late father, John Cheres Arap Sang, my friend and teacher of many years and to my late grandmother, Mariah Tabutany for her love and strong commitment to family. I also dedicate this study to my mother, Grace Tabelgaa Sang for her love and patience during the many years of my studies and overseas travels. Finally yet importantly, I dedicate this study to my wife Subashri Kurgatt, my son Charles Kipkorir Kurgatt and my daughter Stefanie Chepkoech Kurgatt for their love, encouragement and patience.
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ABSTRACT

The purpose of this study was to develop a new methodology of on-line optical spun yarn count analysis and control (OYCA) by use of on-line optical yarn diameter measurements and to carry out method comparison study against the ASTM D 1907 – 89. The result of the study showed sufficient agreement between OYCA and the ASTM D 1907 – 89. Inter-plant comparison of method difference was not significant, which is an indication of the robustness of OYCA across plants with similar technologies and process parameters. Significant predictive relationship between optical yarn volumes (OYV), twist and linear density was demonstrated by a factorial experiment where factors of twist and linear density were set at high and low levels of ±10% augmented by center points from regular production set up. Optical fiber volumes in skeins were verified using gas pycnometer volume measurements. Significant correlation $r(60) = 0.96$, $p<.01$ between fiber volume and OYV was observed. Altman-Bland (1986) test of agreement showed a consistent bias of -0.55. The bias observed was attributed to lower estimation of fiber volume fraction (FVR) and more light transmission through the yarn structure. In practice, the magnitude of the bias observed was not significant and hence The ASTM D 1907 – 89 and OYCA methods exhibited sufficient agreement in spun yarn count analysis.
CHAPTER 1

INTRODUCTION

Quality in textile products is associated with product performance attributes and customer perceptions in the market place. However, global competition continues to redefine textile product quality throughout the textile industry. The principal players in this global marketplace include, but are not limited to, raw material suppliers, product manufacturers, wholesalers, retailers and service industry providers (Dunn, 2003). Individual companies within the textile supply chain specialize in specific textile products such as fibers, yarns, fabrics, chemicals auxiliaries, and dyestuffs. Individual companies within the textile supply chain strive to achieve two basic goals; to meet company business objectives and to satisfy or exceed customer needs (Kadolph, 1998).

Accurate measurements and efficient quality evaluation of textile products are therefore the key elements in meeting customer requirements and achieving the overall company business objectives. Customer needs assessments for every product offered is vital to defining customer needs and understanding the role played by these needs in process control and quality evaluation. The term “customer” within the textile industry elicits differing meanings in different segments of the industry. However, ‘customer’ is generally defined as an entity engaged in the purchase (or by interdepartmental or process within the firm) of one or more of the textile products either for raw materials or for resale to the consumer. During the last decade assumed product differentiation, quick response and accuracy have assumed significant importance in any emerging quality initiatives in the textile industry in addition to efficient management of input factors. Comprehensive raw materials and process certification programs have become important quality assurance tools for excellence in the global textile market place. Product quality attributes deemed to have significant influences on product performance form the primary basis for the manufacturers or vendors quality evaluation.

Globalization, rising energy costs and environmental controls during the past decade have placed substantial demands on firms within the textile industry. Consequently, automation and a push towards on-line quality control systems have taken root in the textile industry (Dunn, 2003).
The capacity to implement on-line based quality control systems in manufacturing of textiles is partly due to a tremendous progress achieved in the development and implementation of electronic instrumentation and sensor technology.

Textile Product Quality

The producer’s perspective of quality historically has been in terms of product process performance, whereas, the consumer’s perspective has been, and continues to be, in respect to overall quality attributes they believed to have significant impact on product performance or application (Kadolph, 1998). A significant number of companies have adopted quality definitions based on total quality management (TQM) that apply throughout their organizational system with a goal of achieving quality standards in their target markets. Target markets are defined as segments of the population with commercial or consumer interest in a given product. Physical or chemical characteristics of products may have direct or indirect influences on one or more quality attributes in a textile product. Product attributes such as aesthetics, durability, serviceability, comfort, care, and cost are good examples of dimensions of quality in textiles (Kadolph, 1998). In the case of yarn products, yarn number and linear density variations, hairiness, imperfections, and yarn diameter are part of measurable yarn quality characteristics essential to yarn quality (Atilgan, 2007).

Yarn Count

Linear mass density, yarn number or yarn count are terms variously used to describe yarn size. Description of yarn size in spun yarns is complicated by lack of perfect cross-sectional shape and surface rigidity. All spun yarns exhibit a certain degree of variability in the cross-sectional diameter. This variability is associated with the inherent spun yarn cross-sectional fiber arrangement properties. Depending on the measurement system, yarn count may indicate mass unit length of yarn or length per unit weight of yarn. Common yarn numbering systems used in different types of yarns and included in the American Society for Testing and Materials (ASTM) test method for yarn linear density ASTM D 1907-89 are listed in Table I (ASTM, 1989). Indirect yarn numbering systems describe yarn size in terms of a standard yarn length per unit of a standard yarn weight. The Cotton System for yarn count is an example of an indirect yarn numbering system with a standard unit length of 840 yards and standard yarn weight of one pound. In direct yarn count systems, yarn count is specified in terms of mass per unit length of
yarn. The International Standards Organization (ISO) has adopted ‘Tex’ (defined as mass of yarn in grams for 1000 meters of yarn) as a universal unit for direct yarn count system.

<table>
<thead>
<tr>
<th>Measurement System</th>
<th>System</th>
<th>Standard Length</th>
<th>Standard weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct System</td>
<td>Tex</td>
<td>1000 m</td>
<td>1 g</td>
</tr>
<tr>
<td></td>
<td>Denier</td>
<td>9000 m</td>
<td>1 g</td>
</tr>
<tr>
<td></td>
<td>Spindle</td>
<td>14400 yd</td>
<td>1 lb</td>
</tr>
<tr>
<td>Indirect System</td>
<td>Cotton Count</td>
<td>840 yd</td>
<td>1 lb</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>100 yd</td>
<td>1 lb</td>
</tr>
<tr>
<td></td>
<td>Linen</td>
<td>300 yd</td>
<td>1 lb</td>
</tr>
<tr>
<td></td>
<td>Metric</td>
<td>1000 m</td>
<td>1 kg</td>
</tr>
<tr>
<td></td>
<td>Woolen</td>
<td>1600 yd</td>
<td>1 lb</td>
</tr>
<tr>
<td></td>
<td>Worsted</td>
<td>560 yd</td>
<td>1 lb</td>
</tr>
</tbody>
</table>

Quality Standards

Product characteristics that have the greatest impact on product performance are used to formulate specific rules or measurable parameters used in process control. These rules or parameters are translated into specifications by prescribing limits or tolerances. Specifications adopted, in part or as a whole, by an individual organization/association, company or industry are referred to as quality standards. Uster® Statistics are standards that pertain to yarn physical properties developed through worldwide surveys of yarn manufacturers by Uster Technologies Inc. Uster® Statistics pertain to fiber and yarn quality characteristics. These standards are specific
to yarn markets for consistent use in yarn process control and market transactions. Uster® Statistics have become the most important and widely used quality standards in spun yarn manufacturing (Atilgan, 2007). Tables II and III describe yarn quality characteristics relating to physical yarn properties used in Uster® Statistics. Collectively, Tables II and III form the basis of spun yarn quality characteristics and their evaluations geared to production process control and market requirements.

Table II

*Spun Yarn Quality Characteristics: Uster® Yarn Standards*

<table>
<thead>
<tr>
<th>Quality Characteristics</th>
<th>Abbreviation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count variation</td>
<td>CV&lt;sub&gt;cb&lt;/sub&gt;</td>
<td>Count variation between packages</td>
<td>%</td>
</tr>
<tr>
<td>Linear mass variations</td>
<td>CV&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Coefficient of variation of mass (8mm)</td>
<td>%</td>
</tr>
<tr>
<td>Mass variations</td>
<td>CV&lt;sub&gt;m&lt;/sub&gt;&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Coefficient of variation of mass between packages</td>
<td>%</td>
</tr>
<tr>
<td>Imperfections</td>
<td>Thick</td>
<td>Number of thick places</td>
<td>1/1000 m</td>
</tr>
<tr>
<td>Imperfections</td>
<td>Thin</td>
<td>Number of thin places</td>
<td>1/1000 m</td>
</tr>
<tr>
<td>Imperfections</td>
<td>Neps</td>
<td>Number of neps</td>
<td>1/1000 m</td>
</tr>
<tr>
<td>Hairiness</td>
<td>H</td>
<td>Absolute value of hairiness</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>S&lt;sub&gt;H&lt;/sub&gt;</td>
<td>Standard deviation of Hairiness within a package</td>
<td></td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>CV&lt;sub&gt;Hb&lt;/sub&gt;</td>
<td>Deviation of hairiness between packages</td>
<td>%</td>
</tr>
<tr>
<td>Trash</td>
<td>Dust, Trash</td>
<td>Dust and trash in yarns per 1000 m of yarn</td>
<td>1/1000 m</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>CV&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Variation of yarn diameter</td>
<td>%</td>
</tr>
<tr>
<td>Shape</td>
<td>Shape</td>
<td>Yarn cross section. Ratio of axes of ellipse</td>
<td></td>
</tr>
<tr>
<td>Yarn density</td>
<td>D</td>
<td>Density of yarn</td>
<td>g/cm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table III

*Spun Yarn Tensile Quality Characteristics: Uster® Yarn Standards*

<table>
<thead>
<tr>
<th>Quality Characteristics</th>
<th>Abbreviation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>$F_H$</td>
<td>Breaking force</td>
<td>cN</td>
</tr>
<tr>
<td>Tenacity</td>
<td>$R_H$</td>
<td>Breaking force referred to yarn count</td>
<td>cN/tex</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>$CV_{RH}$</td>
<td>Variation of individual values of the tenacity</td>
<td>%</td>
</tr>
<tr>
<td>Elongation</td>
<td>$\xi_H$</td>
<td>Yarn elongation at break</td>
<td>1/1000 m</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>$CV_{\xi H}$</td>
<td>Variation of individual values of elongation</td>
<td></td>
</tr>
<tr>
<td>Work done to break</td>
<td>$W_H$</td>
<td>Work performed during tensile testing of yarns</td>
<td>cNcm</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>$CV_{WH}$</td>
<td>Variation of individual values of work done at break</td>
<td>%</td>
</tr>
</tbody>
</table>


**Purpose of the Study**

The purpose of this study was to develop a methodology for an on-line spun yarn count analysis and control in spun yarn manufacturing by application of optical yarn diameter measurements used in the computation of yarn count. Hence, the new method developed in this study is referred to as optical yarn count analysis (OYCA). The effectiveness of the new methodology was assessed by a comparative test against the ASTM Standard Test Method D-1907.
The ASTMD-1907 is an off-line test method globally adopted as a voluntary standard by yarn manufacturers for process control and market transactions (Suh, 1994). The validity of ASTM D-1907 test method results are significantly dependent on deployment of correct and timely sampling techniques. A large number of yarn manufacturers still use the ASTM D-1907 test method for yarn count in conjunction with partial automation in specimen handling and data analysis within the traditional lab setting (Charterjee, Bhattachariyya, & Majundar, 2004). Weighing of specimens is an integral part of the ASTM D-1907 test method and the results are an indication of longitudinal mass variation in the test yarn. Mass variation in spun yarns analyzed with the aid of evenness testing machines provide variability measures based on deviations detected by capacitance, optical or mechanical sensors. Longitudinal mass variation is a component of yarn quality and has an impact on the final product appearance and tensile properties (Kilic & Okur, 2006). Rotor, air-jet spinning and yarn winding technologies have successfully adopted on-line measurements of yarn evenness and defects without the capabilities for analysis of yarn count.

**Rationale**

A study to develop a methodology for an on-line spun yarn count analysis and control in spun yarn manufacturing is significant for several reasons. High cost of production and competitive global markets continue to exert enormous pressure on United States (US) textile manufacturers; this situation has caused a significant number of US textile manufacturers to relocate overseas. The remaining firms struggle to find enough orders to satisfy existing plant capacities (Phillips, 2008). Competitive yarn spinning firms are proactive and address competition pressure through innovations and dynamic business models that include niche market development, vendor partnerships, commitment to high quality products, timely market deliveries, competitive export strategies and product differentiation (Phillips, 2008). Globalization of textile trade in the past decade has placed substantial demands on the supply chain and quality initiatives of individual players in textile markets. Product differentiation, quick response and accuracy are key elements of a competitive quality initiative. Consequently, automation and a push towards on-line quality control is taking root in the U.S. textile industry due to the high costs of textile testing. Product inspection is increasingly becoming more expensive due to the high cost of textile testing (Dunn, 2003) The key factors that drive up the cost of yarn quality control testing are the high cost of equipment purchase and installation,
maintenance, raw materials, salary, wages, and re-works (Saville, 1999). The improved capacity to implement on-line based quality control systems in textiles is in part due to tremendous progress achieved in instrumentation and sensor technology. The present level of developments in computing, sensor technology, and automation have made diagnostic and tele-maintenance capabilities in the textile industry feasible (Rockwell Automation Inc., 2007). Due to global demands for quality textile products, an array of on-line technologies are used in wet processing, fabric and yarn inspection, winding, spinning preparatory, fiber blending, and so forth. The large amount of data involved in on-line tests presents a challenge to textile firms, and to address this problem, Suh (1994) proposed using ‘finger printing’ techniques to capture only extreme deviations. This strategy provides an option for eliminating large amounts of, otherwise meaningless, data points that increase computing costs. A combination of on-line and off-line tests are recommended for spinning firms due to sampling inadequacy in off-line tests and lack of availability of on-line tests on a number of yarn quality characteristics. On-line quality evaluations currently in use in the yarn manufacturing industry use Uster® Ring Expert Systems and similar competing technologies limited to monitoring yarn end breaks, efficiency and idle spindles (Peters, 2003). Relative humidity changes provide drawbacks for capacitive sensor based on-line instruments due to poor sensitivity. However, manufacturers of infra-red optical scanners claim that humidity levels have minimal, if not insignificant, impact on the accuracy of test results. This makes optical scanners good candidates for on-line instrumentation (Zweigle Textilprüfmaschinen, 1997). High costs associated with testing equipment, machine accessories, raw materials, calibration, certification, salary and wages make it very expensive for yarn manufacturers to carry out requisite textile testing and product inspection (Saville, 1999). In order to combat the rising costs of production, textile producers are trending towards process automation. This makes on-line measurements and control of production processes a must for quality and cost control in textile production. The advantages of on-line systems lies in the provision of real and quick opportunities for detection of off-target production units while allowing for timely machine adjustments within the product quality and productivity specifications (Peters, 2003). On-line system deployment has the potential to improve process-sampling capabilities through real time data acquisition, and analysis.
Theoretical Framework

A spun yarn is an assemblage of individual fibers randomly distributed along the yarn axis and held together by a binder or mechanical forces derived from inter-fiber friction and twist. The size of a spun yarn diameter is, therefore, influenced by variation in the cross-sectional fiber density and physical fiber properties. Numerous variations in fiber deposition, stretching, fiber crimp level or twist, make it quite difficult to report yarn size by diameter alone. By assuming constant yarn bulk density, Peirce (1937), developed an empirical functional relationship between diameter, count and bulk density, shown in Equation 1, from microscopic studies of yarn specimens from a sample of ring spun yarns.

Equation 2 is an equivalent formula in metric units in ‘Tex’ for yarn linear density $T$, yarn bulk density $\rho_b$ and average yarn diameter $d$ :

$$d = \frac{1}{28\sqrt{(N_e)}}$$  \hspace{1cm} 1

$$T = 1000. \frac{\pi d^2}{4} \cdot \rho_b$$  \hspace{1cm} 2

El Mogahzy (1993) improved on Equation 1 with the same underlying assumption of constant lengthwise bulk density of spun yarns. In the absence of any assignable causes, longitudinal variations in yarn linear density and diameter are random. Fiber distribution curves plotted from normalized radii values and packing density in spun yarns produced from the same technology and process parameters follow the same curve (Jiang et al., 2005). Therefore, by assuming constant bulk density throughout the yarn length, spun yarn count can be estimated from a series of optically scanned diameters $d$ over the entire length of any given yarn specimen. Fiber volume ratio is required for estimation of fiber volume from bulk yarn volume measured and is reported in terms of yarn diameter. Jaouadi, Msahli, and Sakli, (2009) defined fiber packing fraction $\Phi_f$ as a ratio (equivalent to FVR) of yarn volume $V_y$ to fiber volume $V_f$ expressed as a ratio of yarn density to fiber density. Lawrence (2003) defined FVR as the degree of fiber packing within a given yarn cross-section as shown in Equation 3.

$$\varphi = \frac{V_f}{V_y}$$  \hspace{1cm} 3

The latest optical sensor technologies used in yarn diameter measurements have therefore presented an opportunity to compute yarn linear density from initialized yarn densities and on-line optical yarn diameters. Off-line methods alone are no longer sufficient to capture and detect
rare yarn spinning positions that are running out specifications (Peters, 2003). The role of yarn diameter in yarn quality evaluation, and the significance of high productivity and premium quality demands from the market, has led to the development and adoption of optical yarn diameter measuring devices for off-line yarn uniformity testing machines.

**Objectives**

The purpose of this study was to develop a methodology for on-line measurement and control of spun yarn count (OYCA) through optical yarn diameter measurements based on the empirical relationship between yarn cross-sectional diameters and yarn count. Samples from 100% ring spun acrylic yarns were used in this study. Given this purpose, the objectives of this study were to:

1. Explore the association of optical yarn volume with yarn twist and yarn count in 100% ring spun acrylic yarns that were produced from the same spinning technology and fiber blend at different yarn twist and count levels within ±10% levels.

2. Explore the association of optical yarn volume of 100% ring spun acrylic yarns at different yarn twist and yarn count levels with fiber volume $V_f$ measured by constant-volume gas pycnometry.

3. Determine the impact of different yarn twist and yarn count levels on OYV in 100% ring spun acrylic yarns spun on the same spinning technologies, fiber blend and process specifications.

4. Explore the difference between OYCA and ASTM D 1907-89 Test Methods by using 100% ring spun acrylic yarns produced by three spinning plants running on the same spinning technology, fiber blend and process specifications.

5. Compare OYCA and the ASTM D-1907 yarn count test methods in 100% ring spun acrylic yarns produced by three different plants running the same spinning technology, fiber blend and process specifications on the following conditions:
   a. Different twist levels within ±10% of nominal twist.
   b. Different yarn count levels within ±10% of nominal count.

6. Develop recommendations for on-line yarn linear density analysis and control of production based on the OYCA methodology.
Research Questions

The objectives of this study were satisfied by exploring the following research questions:

Q1. Is there any relationship among OYV, yarn twist and yarn count in 100% ring spun acrylic yarns?

Q2. Is there any relationship between fiber specimen volumes $V_f$ measured using a constant volume gas pycnometer and yarn OYV ‘$V_y$’ in 100% acrylic ring spun yarns?

Q3. Do changes in yarn twist and yarn count within ±10% levels in 100% acrylic ring spun yarns produced on the same spinning technology and fiber blend affect OYCA efficiency in different spinning plants?

Q4. Is there any relationship between OYCA and ASTM D 1907 test methods over the ±10% levels in twist and yarn count in 100% acrylic ring spun yarns produced on the same spinning technology and fiber blend?

Q5. Is there agreement between OYCA and ASTM D 1907 test methods over the ±10% levels in twist and yarn count in 100% acrylic ring spun yarns produced on the same spinning technology and fiber blend?

Q6. Does the OYCA method offer a scope for on-line yarn linear density analysis and control in yarn manufacturing?

Hypotheses

In order to address the objectives of this research, the following hypotheses were tested:

H1. There is no significant relationship among OYV ($V_y$) yarn twist and yarn count in selected 100% acrylic yarns.

H2. There is no significant relationship between yarn OYV and fiber volumes ($V_f$) by constant volume gas pycnometer test method.

H3. Yarn count and twist changes within the production range of ±10% levels do not have any significant effect on OYV in selected 100% acrylic yarns produced in the same spinning technologies, fiber blend and process specifications.

H4. There is no significant relationship between (OYCA) and ASTM D-1907 test methods in determination of yarn linear density of the selected 100% acrylic yarn among plants running similar spinning technologies, fiber blend and process specifications.
There is no significant agreement between (OYCA) and ASTM D-1907 test methods in determination of yarn linear density of the selected 100% acrylic yarn among plants running similar spinning technologies, fiber blend and process specifications.

Scope

The following factors associated with technological capacity and product offering in the participating firms limited the scope of this study.

1. Test specimens sampled from 100% acrylic ring spun yarns of English count 18/1.
2. Short staple fiber ring spinning technology adopted for this study was limited to the equipment available and in operations in the three plants.
3. The range of fiber materials available was limited to 36 mm short staple length and 3.0 denier acrylic fibers.
4. The production parameters of the yarn available for the study were limited by the prevailing plant yarn size and twist to within ±10%.
5. Uniformity of yarn linear density was limited to the prevailing evenness in the respective spinning plants.

Limitations

Limitations of this study that might influence the outcome were:

1. Methodology developed for application in OYCA yarn linear density test method was based on spun yarn diameter measurements obtained from only 100% acrylic ring spun yarns.
2. Lawson-Hemphill EIB yarn diameter measuring equipment was equipped with only one CCD camera device.
3. OYCA test method was dependent on initial determination of fiber volume fraction in the prevailing manufacturing process and fiber properties.
4. Specific to 100% acrylic yarn count utilized by the participating firm.
5. Sample yarns were from three plants of the participating firm.

Assumptions

Assumptions applied in this research study were as follows:

1. The yarns and individual fibers were assumed of perfect cylindrical shape.
2. Individual fibers are randomly distributed in both cross-sectional and longitudinal dimensions in spun yarns.
3. Effects of humidity and hairiness have negligible effect on optical yarn diameter.
4. Light transmission through the fibrous yarn structure is constant for a given fiber blend and yarn structure.

**Terms and Definitions**

The following terms and definitions are presented for clarifications of the text in this study:

**Count Variation:** Measure of variation in yarn count between independent samples (Bobbins, machines, etc) and expressed as a ratio of standard deviation and average of yarn count.

**Doubling:** The number of sliver strands drawn together in a drawing operation in order to improve lengthwise uniformity of produced sliver (Oxtoby, 1987).

**Drafting:** The process of attenuating and blending individual sliver strands through series of nipping points due to a series of paired rollers where front roller pairs set to run at higher surface speeds than the back rollers cause individual fibers to slide past one another (Oxtoby, 1987).

**Fiber Density:** Fiber density is mass per unit volume of fiber (Joseph, 1966).

**Fiber Volume Ratio (FVR):** The ratio of fiber volume (initially estimated from known fiber volume of a given length of yarn) and optical yarn volume computed from average yarn diameter.

**Imperfections:** Imperfections are frequency and size of events deviating from the normal spun yarn specifications categorized into classes in 1000 meters of yarn. The imperfections are classified as Neps for an event size of +200%, thin places for event size of -50%, and thick places for event size of +50% of the nominal yarn diameter. Due to structural differences between rotor and ring spun yarns, their classification based on imperfections fall under different yarn standards (Uster Technologies AG, 2006).

**Mass Variation:** Yarn quality parameter used to describe longitudinal variations in yarn mass.

**Optical Yarn Count Analysis (OYCA):** Determination of yarn count from the product of fiber volume ratio (FVR), optical yarn volume (OYV) computed from average optical yarn diameter and fiber density.

**Optical Yarn Volume (OYV):** The volume of a yarn specimen computed from optical yarn diameter by assuming perfect cylindrical properties in yarn structure.

**Ring Spun Yarns:** Yarns produced from staple fibers using ring spinning machines where twist
insertion is by action of a ring, traveler and a revolving spindle carrying a tube over which the produced yarn is wound. The traveler speed lags against the spindle to generate the required winding speed (Oxtoby, 1987).

**Spun Yarn:** A continuous series of fibers randomly spread in the yarn and held together by strands of twisted fibers assisted by inter-fiber friction and individual fiber migration across different yarn radial positions (Oxtoby, 1987).

**Skein:** A continuous strand of yarn of specific length required as a sample length for determination of yarn count and tensile strength usually wound with a large circumference in relation to its thickness (ASTM, 1989).

**Tensile Properties:** Tensile properties of yarns include breaking force, breaking tenacity, elongation and work-to-break. Averages and coefficients of variations are analyzed and reported as yarn physical quality parameters (ASTM, 1989).

**Textile Strand:** Is an ordered assemblage of textile fibers, single fibers, filaments or monofilaments used singly or in plurality and having high length to diameter ratio (ASTM, 1996).

**Twist Factor:** The product of twist in turns per centimeter and square root of yarn count expressed in Tex (ASTM, 2008).

**Yarn Bulk Density:** Ratio of yarn mass in a unit specific volume of yarn (Goswami, Martindale, & Scardino, 1977).

**Yarn Count:** Yarn count is an indication of weight of a known length of yarn expressed as mass per unit length or length per unit mass as a measure of yarn size. International organization for standardization (ISO) has adopted ‘Tex’, which is mass per unit 1000 meters of yarn- as a universal system for describing yarn size (Oxtoby, 1987).

**Yarn Hairiness:** A measure indicative of the length and number of all fibers protruding from a yarn surface. Both within and between sample coefficients of variation are calculated during yarn hairiness test (Uster Technologies AG., 2010).

**Yarn Imperfections:** A count of the number of defects within a specified yarn length. Yarn defects are defined in relation to average yarn diameter. Thick and thin yarn places are examples of yarn imperfections (Goswami et al., 1977).

**Yarn Irregularity:** A measure of lengthwise variations in the distribution of constituent fibers in spun yarns (Goswami et al., 1977).
CHAPTER 2

LITERATURE REVIEW

Within the textile industry, yarns processed from fibrous raw materials are used in the fabrication of fabrics and other industrial textile products. Raw materials for textile yarns range from polymeric filaments, synthetic staple fibers, multiple fiber blends, to natural fibers. In general, a spun yarn is a product of staple fibers converted into yarn by a spinning process. Spun yarn spinning processes are designed to attenuate and randomly arrange individual or groups of fibers and bind them through the action of twist or binder into a continuous textile strand. Different techniques such as ring, rotor and air-jet spinning, among others, are used in the production of spun yarns. Each of these techniques produces yarns of vastly varying quality characteristics, performance, appearance, and cost. Type and grade of fibers used in yarn manufacturing will also determine the resulting quality levels in the final product.

Modern Yarn Production Process

Modern processes employed in short staple spun yarn production is comprised of a series processes that include fiber opening, fiber cleaning, carding (fiber opening and individualization), drawing (sliver and roving), ring spinning and winding. Product quality and throughput rates are controlled by adhering to spinning specifications designed to optimize product quality and productivity. Quality characteristics of spun yarns include linear density, uniformity, defect rate, hairiness, foreign matter, tensile properties and color.

Figure 1 illustrates a fiber-to-yarn conversion process designed for high quality acrylic spun yarn production. Each process plays a unique function and contributes to the final yarn quality. The desired throughput efficiencies and productivity vary widely between yarn types and spinning firms. Linear density variations in yarn spinning firms are controlled by drawing and sliver end doubling followed by targeted draft adjustments. Modern drawing machines employ highly sensitive auto-leveling devices capable of regulating sliver irregularities to within ± 2% of the desired levels using thickness sensors that actuate drafting mechanism on the feed sliver (Azzam & Mohamed, 2005).
Figure 1: Spun yarn fiber-to-yarn conversion process.

Note. (a) Fiber opening/Cleaning; (b) Carding; (c) Drawing; (d) Roving; (e) Ring spinning; (f) Winding
Table IV
Spun Yarn Process and Quality Characteristics in Preparation

<table>
<thead>
<tr>
<th>Process</th>
<th>Process requirements</th>
<th>Quality Characteristics</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening</td>
<td>Fiber opening</td>
<td>Weight of fiber assembly</td>
<td>g/m</td>
</tr>
<tr>
<td></td>
<td>Cleaning</td>
<td>Uniform fiber assembly</td>
<td>cv%</td>
</tr>
<tr>
<td></td>
<td>Homogeneous blending&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No fiber damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carding</td>
<td>Fiber individualization</td>
<td>Sliver size</td>
<td>g/m</td>
</tr>
<tr>
<td></td>
<td>Drafting, Cleaning&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Uniform linear density</td>
<td>cv%</td>
</tr>
<tr>
<td></td>
<td>Homogeneous blending</td>
<td></td>
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<tr>
<td></td>
<td>Fiber web condensing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawing</td>
<td>Attenuation and individualization</td>
<td>Sliver size (g/m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sliver mass uniformity improvement</td>
<td>Uniform linear density</td>
<td>cv%</td>
</tr>
<tr>
<td></td>
<td>Attenuation and individualization</td>
<td></td>
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<tr>
<td></td>
<td>Sliver mass uniformity improvement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roving</td>
<td>Reduction in sliver size</td>
<td>Roving size and Uniformity</td>
<td>g/m, cv%</td>
</tr>
<tr>
<td>Twisting</td>
<td></td>
<td>Number of turns</td>
<td>Turns/Inch</td>
</tr>
</tbody>
</table>

Note. <sup>1</sup> Blending is required for all fiber blends particularly important when different fibers or colors are used.

<sup>2</sup> Cleaning used in lines designed to process cotton fibers.
Table V

*Spun Yarn Process and Quality Characteristics in Spinning*

<table>
<thead>
<tr>
<th>Process</th>
<th>Process requirements</th>
<th>Quality Characteristics</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinning</td>
<td>Roving size reduction</td>
<td>Final yarn size</td>
<td>Tex</td>
</tr>
<tr>
<td></td>
<td>Linear mass</td>
<td>Yarn mass uniformity</td>
<td>cv%</td>
</tr>
<tr>
<td></td>
<td>Twist</td>
<td>Yarn twist level</td>
<td>tpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Twist uniformity</td>
<td>cv%</td>
</tr>
<tr>
<td>Winding</td>
<td>Yarn winding onto cones</td>
<td>Yarn package size</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td>Clearing defects</td>
<td>Defects per unit weight of yarn</td>
<td>defects/Kg</td>
</tr>
</tbody>
</table>

**Process Control**

Managers experienced in total quality management note that achieving a positive synergistic effect from a host of input parameters and product attributes is a pre-requisite to producing high quality goods. (Winchester, 1994). To sustain and even grow their market share, yarn manufacturers consistently produce yarns at slightly higher specification limits than those articulated in the customer’s order. Yarn manufacturers have invested heavily in innovative technologies in fiber evaluation systems, such as high volume instruments and evenness testers for measuring and analyzing fiber and yarn quality parameters.

**ASTM D-1907 Test Method for Yarn Count**

The ASTM D-1907 method is a manual process that is essentially a “cut and weigh” method. A fixed length of yarn unwound from a sample package or drawn from a fabric specimen is weighed on a standard yarn count scale or balance. Weight per unit standard length of yarn is computed based on a given yarn size numbering system. Yarn samples are conditioned and specimens are prepared for testing. Coefficient of variation (CV) in yarn count is computed from yarn specimen count data. Advanced technologies such as Uster Advanced Fiber
Information System (AFIS) and Uster High Volume Instruments (HVI) are widely used by yarn manufacturers for measuring and analyzing yarn quality parameters. Linear density variations in individual sliver strands are determined in key production stages of a spun yarn spinning process.

Uniformity in yarn linear density is a key spun yarn quality parameter with significant contributions to performance and quality of fabrics. The value of CV in linear density is a measure of uniformity or irregularity in yarns. The number of fibers per cross-section of highly even yarns must be close to a constant (Martindale, 1942). Due to the significance and role of uniformity in yarn linear density, different techniques employing optical and capacitive sensors developed for continuous characterization of sliver quality parameters are currently in use by leading spun yarn manufacturers. Auto-leveling devices installed in carding and drawing machines can automatically sense deviations and effect instantaneous change of sliver fiber mass density. Doubling of slivers in a drafting operation can result in a reduction variation in sliver density. A root factor of the number of sliver doubling gives a good estimate of improvement in sliver CV. Improvements in variation of sliver count results when process induced variance is lower than variance due to doubling (Tippett, 1935; Martindale, 1942).

Yarn Count Control

Product specifications controlled in yarn manufacturing plants following established quality procedures and protocol in each of the spinning processes are shown in Table II. Product specifications in each process step are described in terms of weight per unit length controlled by means of machine adjustments triggered through product quality evaluation. Figure 2 is an illustration of an off-line yarn count measuring equipment installed in a conventional yarn manufacturing plant with data handling and analysis facilitated by the use of an analytical balance and a computer.
Testing for Spun Yarns

The quality objective of the yarn manufacturing process is to produce a product whose size and variability is within established specification limits. Developments achieved in optical yarn diameter measurements will provide alternative methods for spun yarn appearance grading. Kim, Langley and Avsar (2006) used Lawson-Hemphill Yarn Analysis System (YAS) equipped with a charged coupled device (CCD) video camera and a constant tension and transport (CTT) device to measure and capture digital representation of spun yarn diameter variations in motion. In the YAS system, yarn speed of 100m/min will capture yarn diameter values from test yarn segments 0.5mm long. Appearance indices designed to discriminate yarn appearance grades in spun yarns were then developed based on optical yarn diameter, CV% of yarn diameter and yarn imperfections (Kim, Langley, & Avsar, 2006).
Capacitance and optical methods have gained considerable market share in yarn manufacturing by Zellweger, Uster, Zweigle and Lawson-Hemphill (Saville, 1999). In addition to yarn evenness and imperfections, yarns are tested for mechanical properties, twist hairiness, and to a limited extent, chemical properties, if not already established through fiber properties. Mechanical properties are part of yarn physical tests carried out using laboratory equipment and hence, not available for on-line testing, although they have been extensively automated. Evaluation of yarn tensile property techniques are specimen destructive and unsuitable for carrying out on-line tensile.

**On-Line Measurements and Control of Yarn Count**

There is a need for on-line measurements and continuous monitoring of yarn quality parameters in real time to reduce the need for expensive off-line quality tests. Application of capacitance and optical techniques in on-line evaluation of yarn quality is beginning to take root in the textile industry, particularly in respect to yarn imperfections.

Yarn diameter has become an important yarn quality parameter with significant influence on value and quality of produced fabrics. Objective evaluation methods for yarn appearance are slowly emerging as optical yarn diameter testing machines gain industry wide acceptance. Quantitative methods based on yarn diameter measurements recently have been developed and applied to the grading of spun yarns appearance (Kim et al., 2006). Yarn evenness and yarn diameter are useful in predicting and manipulating the final fabric appearance and functionality. Yarn evenness and incidence of yarn quality characteristics have successfully been converted to on-line measurement and widely used in sliver preparation, and rotor and air-jet spinning technologies (Charterjee et al., 2004).

In addition to spinning, weaving and wet processing have also has made progress in on-line testing and control. Testex FX 3250 is an automatic pick-counter designed for on-line measurements and control fabric pick density in weaving. Profilair FX 3386 air permeability tester is designed for integration into the production line and has the capacity to monitor and initiate corrective action on out-of-specification web density data in nonwoven production (Dunn, 2003). On-line inspection for yarn quality attributes such as evenness, imperfections, efficiency, production, yarn faults, among others in yarn winding operations, can be analyzed and managed using Uster® Quantum Clearer (Peters, 2003). Uster® Sliver Guard is another
system developed by Uster Technologies for on-line monitoring and automatic control of sliver count. Technologies available for on-line tests and monitoring in preparation departments are equipped to provide 100% on-line testing for sliver count, evenness, periodic faults, and thick places (Zellweger Uster, 2000).

**Optical Sensors in Yarn Inspection**

Yarn optical inspection sensors use systems equipped with line scan cameras to measure and analyze transmitted light flux. Total flux falling on the receiver is compared to the emitted flux in order to generate an image or shadow of a dynamic yarn. This process is a combination of digital and analog sensors operated synchronously. A transmitter emits a near parallel light beam projected across the yarn path. Obstruction of the beam by the dynamic yarn causes the photo sensor, equipped with application specific integrated circuit (ASIC), to sense a lower flux than the emitted flux which is then evaluated to obtain the effective yarn diameter. This principle is used in electronic inspection board (EIB) systems. It has only one charged couple device (CCD) camera and a light source system. The camera captures and projects yarn diameter images to a computer. The principle used in EIB system is illustrated and discussed in the methods chapter of this study.

**Uster® OM**

Figure 3 is an illustration of Uster® Tester 4-SX, a high resolution line scan camera equipped with an Uster® OM sensor which operates on dual image resolution principles. Two transmitters and two receivers are used to generate two yarn images from two receivers. The yarn images are used to evaluate a more accurate mean yarn core diameter to reduce inherent disturbances occasioned by none-circular yarn cross-section.

Interpretation of yarn diameter measurements should be done within the context of yarn structural properties. Assumptions made in measuring yarn diameter presume that perfect cylindrical dimensions are only estimations at best. The development of Uster® OM sensor technology was an attempt to address variations in yarn shape by integrating image projections from two sources of light. The outputs from two-dimensional opto-electronic devices provide an average diameter including a dimensionless value that is a measure of yarn roundness (Uster Technologies AG, 2001).
Figure 3: Measuring principle of the Uster® OM sensor used Uster® Tester 4-SX.


Spun Yarn Twist

A spun yarn is an assemblage of individual fibers held together by binding forces due to the action of twist on individual fibers. In the absence of twist, a chemical binder binds individual fibers together along the yarn axis. Conventional staple fiber spinning systems employ twist to impart coherence and tensile integrity on the spun yarn (Hearle, 1969). Among the list of yarn quality parameters, twist ranks second after yarn count in terms of significance due to impact of final yarn performance (Lawrence, 2003). Characterization of twist in spun yarns is generally completed by using four distinct factors: direction of twist, amount of twist, twist multiplier, and twist angle. In practice, spun yarn manufacturers test for twist level and direction as part of routine quality control. A basic twist tester is all that is required to test for twist direction and twist level. Twist multiplier is a calculated parameter while twist angle is measured by use of a standard laboratory microscope. If fibers show a spirality in counterclockwise
direction yarn twist is classified as ‘Z’ twist and ‘S’ twist for a spirality in clockwise direction. ASTM 1422-99 (2008) is the standard method for measuring twist in single yarns using the untwist-retwist principle. This method carries an associated error due to fiber slippage at the point of lowest twist. Direct counting method is used when more accuracy is required. A number of Electronic Twist Testers (ETT) include options for either direct twist test by rotational counting or untwist/re-twist test method. In addition to method selection, ETT machines are programmed to generate simple statistical reports such as average, standard deviation, and maximum/minimum result data, which may be transmitted directly to a computer or printer. In this study, IET and Zweigle Automatic twist testers determined single yarn twist using untwist-retwist method. Figure 4 illustrates a twist setup using a Zweigle automatic twist tester.

Figure 4: Zweigle automatic twist tester.
Picture by: David Kurgatt

Twist levels measured in terms of twist multiplier and yarn count are the standard parameters referenced by both yarn manufacturers and vendors. Yarn twist represented by the number of turns per unit length of yarn is proportional to the tangent of twist angle ‘θ’ between the fiber and the yarn axis. Figure 5 is an illustration of yarn twist angle in spun yarns and
average yarn diameter represented by ‘D’ and ‘L’ represents the length of yarn per turn of fibers on the surface of the yarn.

The relationship of twist angle ‘θ’, yarn diameter ‘D’ and yarn length ‘L’ is defined in Equation 1.

$$\tan \theta = \frac{\pi D}{L} \quad 1$$

![Diagram of twist angle in spun yarns](image)

Figure 5: Illustration of twist angle in spun yarns.

Fiber length per turn by individual fibers is expressed as a function of twist level in Equation 2. It is evident from Equations 2 and 3 that twist angle is directly proportional to the product of twist and yarn diameter where ‘π’ is the proportionality constant. From the empirical studies by Peirce (1937) and Hearle et al., (1969) we note that yarn diameter is proportional to the root of yarn count ‘C’ and twist angle ‘tanθ’ expressed in terms of yarn count ‘C’, yarn diameter ‘D’ and yarn length ‘L’ as shown in Equation 3.

$$\text{Twist} = \frac{1}{L} \quad 2$$

$$\tan \theta = \alpha \frac{\pi D}{\sqrt{C} L} \quad 3$$

Twist factor (TM) deduced from Equation 3 is referred to as ‘twist multiplier’ and indicates twist magnitude or level. Twist multiplier is a function of the yarn count system and hence, the units of twist, (either turns per inch or turns per meter). Twist factor values illustrate the level of twist in yarn, where higher values indicate high twist and vice versa. Nominal factors of twist levels in
different types of ring spun yarns range from 3.0 to 4.5 where the latter is used in crepe yarns and the former in weft yarns.

Fiber Packing

Influence of fiber twist on fiber packing and its influence on yarn physical properties are dependent upon the spinning process (Jaouadi, Msahli, & Sakli, 2009). The outputs in yarn diameter measurements are dependent upon the method used. Consequently, researchers adopt or apply different terms to describe yarn diameter. Jaouadi et al. (2009), in their study of the effect of twist on yarn diameter, used the term ‘apparent diameter’ in reference to calculated yarn diameter and the term ‘real diameter’ to describe yarn diameter determined by microscopic measurements. Optical and image analysis are methods available for yarn diameter measurements. Each of these methods yields different yarn diameter values that may be misleading if not properly interpreted. Optical methods observed in this study yield yarn diameter values that may be subject to fiber tint. Spun yarn diameter obtained is proportional to the real diameter described by microscopic studies and is consistent within individual yarn specimens, fiber blend or spinning process.

Structural fiber arrangement within the yarn structure have a significant influence on yarn physical properties and studies have shown a significant correlation coefficient between twist and yarn diameter (Kilic & Okur, 2006). Limiting yarn bulk density is achieved with increasing twist, and at maximum twist, yarn bulk density has been shown to correspond to fiber density. For example, when all air spaces within the yarn structure are expelled, yarn bulk density will be equal to fiber density (Jaouadi et al., 2009).

Determination of Fiber Density by Pycnometer Method

Yarn structure is comprised of fiber volume and voids volume. Fiber to yarn volume fraction in spun yarns is therefore always less than 1.0. Accurate determination of fiber volume in spun yarns is a cumbersome process involving sophisticated laboratory equipment. Gas pycnometer offers the best possible method for accurate determination of fiber density using volume measurements by gas displacement method. Liquid pycnometry is an option to gas pycnometers if the liquid used does not interact with the specimens.

Archimedes’s principle is employed in both gas and liquid pycnometers (equal volume by displacement). Helium pycnometry is widely used in research studies to measure fiber density
void volume fractions of polymeric composite materials (Rude, Strait, & Ruhala, 2000). Fiber and void volume fractions are important quality indicators in composite materials. Micromeritics helium gas pycnometer operates on the principle of change in pressure due to volume change in a gaseous medium. All gas pycnometers use the working principle illustrated in Figure 6 (Micromeritics, Inc., 2001).

By applying the gas law illustrated in Equation 4, the unknown volume $V$ can be determined.

$$PV = nRT$$

Where $P =$ prevailing pressure, $V =$ unknown volume, $R$ is the gas constant, $T =$ the equilibrium temperature and $n =$ the Avogadro’s number. When the valve is in the closed position, the two chambers are independent and will exert individual pressure ($P_s$ and $P_r$). When the valve is switched to open, the two chambers merge into a unitary system with pressure adjusting to $P_{sys}$. Equation 5 describes the initial conditions prevailing in the sample chamber with specimens of unknown volume $V_f$. Pressure $P_s$ and $P_r$ in chambers $V_s$ and $V_r$ are such that $P_r$ is greater than $P_s$.

$$P_s(V_s - V_f) + P_rV_r = nRT$$
After the selector valve is switched open, the system starts to equilibrate to a new system wide pressure $P_{sys}$ illustrated in Equation 6. By combining Equations 4 and 5, it is then possible to determine $V_f$ the volume of fiber specimens in the sample chamber.

$$P_{sys}(V_s + V_r - V_f) = nRT$$

Extraneous factors that can lead to changes in pressure are moisture in sample, ambient temperature, and gas leaks. These factors were controlled for accurate results. Micromeritics helium pycnometer provides options for fiber density or volume output along with the number of repeats or cycles in a run and results are presented in a simple statistical report. In this study, fiber volume was selected for assessment and verification of optical volumes of yarn specimen computed from their average optical yarn diameter.

**Yarn Structure**

Previous studies on fiber packing density in spun yarns have revealed a functional relationship between yarn count, twist and diameter (Kremenakova & Militky, 2004). Yarn structure is a key parameter useful in interpretation and application of optical yarn diameters relative to yarn physical properties. Arrangement, density and alignment of individual fibers determine the extent and contribution to yarn tensile properties. Cybulska and Goswami (2001) examined the impact of yarn structure on tensile properties of ring, air-jet, rotor, and vortex yarns. Each yarn type examined exhibited unique failure features. Yarn structures differ from each other mainly due to unique constructional parameters relative to fiber arrangement and orientation within the body of the yarn. Fiber distributions in the core and on the surface are distinctly different. Twist level and count affect yarn diameter, twist angle and fiber migration. Production technology in cotton yarns have significant influence on yarn structural and yarn physical properties (Kremenakova & Militky, 2004). Many studies on yarn structure have also shown that fiber packing coefficients are a function of yarn diameter, yarn linear density, fiber density and shape (Jiang, Huh, Cheng, and Postle, 2005; Yilmaz, Goektepe, 2007; Voborova, Garg, Neckar, and Ibrahim, 2003). Huh, et al. (2002) studied yarns from three technologies, (Ring, Rotor and Friction Spinning systems) and found that yarn packing densities between the technologies differed significantly.
Assuming circular cross-section in spun yarns, Peirce (1937) found a functional relationship between yarn diameter ‘d’, yarn bulk density, linear density ‘ρ_y’ and constant k as shown in Equation 7.

\[ d = k \sqrt{\frac{L}{\rho_y}} \]  

Equation 7 provides a method for estimating average longitudinal fiber packing density in small lengths of yarn. Knowledge of yarn structural properties together with continuous access of information on yarn diameter presents an opportunity for on-line control of yarn uniformity. Kim, Jasper, and Suh (2004) compared mass variation in CV% with optical diameter variation in CV% and found a very strong correlation between these two values. Their findings support the hypothesis that yarn linear density can be estimated in inches from optical yarn diameter (different from microscopic yarn diameter).

Capacitive and optical yarn evenness testers use different measuring fields to determine yarn evenness. Uster 3® and Uster 4® yarn evenness testing machines employ a capacitive field of 8mm length (Uster Technologies AG, 2006). While the Zweigle G-580® yarn evenness testing machine, based on optical diameter measurements, has a test field of 2mm (Zweigle Textilprüfmaschinen, 1997). Kim, et al., (2000) investigated the effect of measuring principle and field on yarn uniformity measurements. The results were adjusted for field size, and the calculated CV values when compared between capacitive and optical scanners, revealed a very strong correlation between CV of mass and optical diameters. The ASTM D 1907 standard provides a tolerance of ±3% for the mean and ±4.8% CV for yarn number, which is 1.4 times the prevailing industrial values.

Cross-sectional and longitudinal fiber distributions within a yarn structure have a functional relationship with yarn physical quality parameters. Knowledge of yarn structure has enabled researches to explain differences exhibited in yarns formed from across spinning technologies. Investigations of yarn cross-sections in various types of yarns have revealed that fiber packing density distributions decrease with increasing radius from the yarn core; it is highest with unique curves in yarns produced from similar spinning technologies (Grishanov, Lomov, Casydy, & Harwood, 1997; and Neckar et al., 1988). Rotor spun yarns exhibit higher uniformity due to a unique twist insertion technique that leads to a yarn core with parallel fibers held tightly by wrapper fibers. Jiang et al. (2005) demonstrated, using equal-area zones, that fiber density distribution in yarn cross-sections of rotor spun yarns is a function of yarn radial position.
and is similar for all rotor spun yarns. The study further demonstrated that higher twist factors result in overall higher fiber packing densities. Coarser yarns had higher overall packing densities when contrasted against finer yarns in the same fiber blend.

According to Peirce (1937), yarn linear density can be estimated from its diameter with a given constant yarn bulk density. Equation 8 is a variation of Peirce’s (1937) equation relating yarn linear mass density Tex ($T$), yarn bulk density ($\rho_b$) and average yarn diameter ($d$):

$$ T = 1000. \frac{\pi d^2}{4} \cdot \rho_b $$

Equation 8 assumes cylindrical yarn dimensions with uniform bulk density $\rho_b$ and normally distributed diameters along the yarn axis. In order to determine the weight of a yarn section spun from fibers of known mass density ($\rho_f$) and fineness, fiber packing fraction, volume ratio, or fiber volume ratio (FVR), ($\phi$) defined in Equation 9 is required.

$$ \phi = \frac{v_f}{v_y} $$

Fiber volume ratio is a dimensionless factor and independent of yarn count and is therefore useful in assessing bulkiness in various yarns. Spun yarns from similar fibers, spinning technology and process parameters exhibit similar structural characteristics and equal FVR.

**Assumptions**

The study of fiber packing in the yarn cross-section has the following various models based on the following assumptions (Lawrence, 2003):

1. Yarn cross-section is composed of large numbers of fibers
2. Central fibers within the core lie parallel to the yarn axis
3. Inter-helical twist of fibers twist around the preceding set of fibers
4. Helix angle is a function of twist
5. Twist is constant along the yarn axis
6. Fibers lie perpendicular to the yarn cross-section
7. Fiber packing density is constant through the yarn length
8. The yarn cross-section is circular filled with concentric circular layers

Figure 7 illustrates fiber radial packing based on equal radial distance and equal area method used to study and analyze cross-sectional fiber distribution in spun yarns. Jiang et al., (2005) used equal area annular rings to study a cross-sectional packing density in rotor spun yarns. Their
findings indicated non-uniform fiber distribution with radial position. Figure 8 shows radial packing curves obtained from samples of 18 singles yarn used in the study. An average curve plotted and used to deduce a cubic function of fiber packing density with respect to radial position from the yarn center as a ratio of yarn radius (Jiang et al., 2005).

Figure 7: Fiber radial packing based on equal radial spacing and equal area method.


Figure 8: Fiber radial distribution curves in 18/1 rotor spun yarn.

Volume and Density Determination

A common method to determine fiber density is by gravimetric methods that use a pycnometer with gas or mercury displacement volumes. Vibroscopic techniques is another method that is available for fiber density determination with a single fiber under tension and of known length is subjected to oscillatory forces at varying frequencies until resonance is achieved. In this study, a pycnometric method using inert gas to provide an alternative method of verifying computed linear densities from optical yarn diameter and nominal fiber packing densities.

Gas pycnometer operates on the principle of pressure change due to displacement of gas by a solid object (Micromeritics, Inc., 2001). A sample chamber, with known fixed volume \( V_s \), is sealed after an object of unknown volume \( V_u \) is introduced. Pressure \( P_s \) in the sample chamber is then measured. A control chamber of volume \( V_c \) adjacent to the sample chamber is then pressurized to pressure \( P_c \) so that \( P_c > P_s \). The two chambers are linked together via a control valve that is used to allow the chambers to equilibrate. By applying the gas law, \( PV = nRT \) the sample volume \( V_u \) is determined. Density is then calculated by dividing the sample mass by volume \( V_u \).

Assuming partial pressures in the combined chamber system is \( P_{cs} \) then:

Prior to linking the two chambers, the condition shown in Equation 10 will prevail:

\[
P_s (V_s - V_u) + P_c V_c = nRT \tag{10}
\]

Equation 11 shows linked chambers with the prevailing conditions of constant temperature and pressure.

\[
P_{cs} (V_s + V_c - V_u) = nRT \tag{11}
\]

The unknown volume \( V_u \) is obtained by solving Equations 10 and 11 thus:

\[
V_u = \frac{P_{cs} V_s + P_{cs} V_c - P_s V_s - P_c V_c}{(P_{cs} - P_s)} \tag{12}
\]

The volume ‘\( V_u \)’, determined in Equation 12 gives the volume of fibers present in a yarn specimen. Density computed from ‘\( V_u \)’ is expected to be statistically equal to actual fiber density value and constant for different values of ‘\( V_u \)’.
In this study, OYCA involves the determination of fiber volume by applying FVR to the optical yarn volume. The most appropriate result verification method is through pycnometric volume measurement. This detects deviations due to ideal yarn assumptions and errors associated with yarn shape factors.
CHAPTER 3

METHODOLOGY

The purpose of this study was to develop an empirical methodology for on-line yarn count analysis and control using optical diameter measurements of dynamic longitudinal sections of spun yarn. Theories related to fiber distribution in a yarn cross-section, as a function of normalized yarn radius, takes into account an assumption of uniform longitudinal distribution. The output from the Lawson-Hemphill yarn analyzer includes average diameter and its coefficient of variation. Optical yarn analysis systems currently in use for yarn appearance evaluation and yarn evenness are based on yarn diameter measurements.

The ASTM test method D 2258-94 is standard practice for samplings of yarn for testing. The standard provides guidelines for drawing samples of yarn from different sources of bulk, ranging from production machines to small fabric specimens, with the objective of obtaining an unbiased estimator for average bulk count. Selection, drawing, and sample size are key factors in sample selection. Population, size, source of the yarn or the target population parameter of the desired quality measured determines the type of sampling and sample size for yarn testing. Sampling skeins for yarn linear density measurement from a production process would be different from sampling cones from a supply or yarn pieces from a sample fabric. ASTM Test Method D 1907 provides tolerance levels based on sample size used to enable detection of significant deviations in size and quality from the norms. ASTM Test Method D 1907 was used to determine average yarn count and coefficient of variation in skein weight.

Research Design

Yarn Sampling

Yarns in this study were sampled from three spinning plants A, B and C located in the states of South Carolina and North Carolina engaged in production of single ring spun yarns from 100% acrylic fibers. For the purposes of this study, the plants were designated as Burlington (A), Norlina (B), and Anderson (C). The ASTM Test Method D 2258-94 was used to sample 40 part cones of yarn in each plant from a current production lot of 18/1 English count
100% acrylic yarn. All three spinning plants studied produced the same yarn count under the same process parameters and technology outlay and differed only in color blends depending upon the prevailing product requirements. Further samples of 10 part cones were drawn from the Burlington plant with spinning frames running 18/1 100% acrylic and set for ±10% on twist and yarn count. Samples with a twist setting parameter of +10% TPI were designated High Twist (TH) and samples with +10% count were designated High Yield (YH) according to the English yarn numbering system. If both twist and count were set at +10% then the sample code designated high twist and high count “THYH.” For a sample with only one parameter changed (Twist or Count), the parameter that remained at standard level is not indicated or coded. The letter “R” and a single letter designates the originating spinning plant and samples from regular production under standard process parameters. Table VI presents yarn product coding used to differentiate yarns according to process parameters and the spinning plants.

Table VI

Sample Set Parameters on 18/1 100% Acrylic Yarn by Spinning Plant

<table>
<thead>
<tr>
<th>Source</th>
<th>Ring Frame Settings</th>
<th>Color</th>
<th>Code</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norlina (B)</td>
<td>Std TPI, Std Count</td>
<td>Black</td>
<td>RB</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>Std TPI, Std Count</td>
<td>Natural</td>
<td>RA</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Anderson (C)</td>
<td>Std TPI, Std Count</td>
<td>Beige</td>
<td>RC</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>-10% TPI, Std Count</td>
<td>Natural</td>
<td>TL</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>+10% TPI, Std Count</td>
<td>Natural</td>
<td>TH</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>Std TPI, -10% Count</td>
<td>Natural</td>
<td>YL</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>Std TPI, +10% Count</td>
<td>Natural</td>
<td>YH</td>
<td>40 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>+10% TPI, +10% Count</td>
<td>Natural</td>
<td>THYH</td>
<td>10 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>+10% TPI, -10% Count</td>
<td>Natural</td>
<td>THYL</td>
<td>10 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>-10% TPI, -10% Count</td>
<td>Natural</td>
<td>TLYL</td>
<td>10 Part cones</td>
</tr>
<tr>
<td>Burlington (A)</td>
<td>+10% TPI, +10% Count</td>
<td>Natural</td>
<td>THYH</td>
<td>10 Part cones</td>
</tr>
</tbody>
</table>

Notes: Settings ±10% Count and vice versa settings represents a yarn yield 10% heavier or lighter than the standard count of 18/1 English system. The same interpretation applies to twist.
**Yarn Count Testing**

The evaluation of yarn count was conducted following ASTM Test Method D 1907. Two skeins of 60 yards were drawn from each sample cone using an automatic multi-skein machine set up to run 8 cones (Figure 9). Each skein was coded following the sample codes in Table VII with actual cone number and letters ‘a’ or ‘b’ used to designate replication. For example, the first skein specimen drawn from cone number 36 of ‘THYH’ yarn sample was therefore designated ‘THYH36a’. This type of coding was necessary in order to associate specimen skein weights and their individual pycnometric skein volumes. Each skein weight was determined using the analytical balance shown in Figure 10 in an air-conditioned laboratory at 21±2°C and 65% ±5% RH according to ASTM D1776 test method. Count evaluation results summarized in Table VII.

![Automatic multi-skein machine](image)

*Figure 9: Automatic multi-skein machine.*

**Notes:** The multi-skein machine is equipped with auto-stop yard length counter and with a collapsible swift to allow skein withdrawal.
Figure 10: Mettler P1000 analytical scale.

Notes: A suitable container cup used to accommodate 60-Yard skeins.
Table VII

Summary of Count Test Results by ASTM D 1907-89 Method

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Size (N)</th>
<th>Mean count (Tex)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>40</td>
<td>32.15</td>
<td>0.25</td>
</tr>
<tr>
<td>RA*</td>
<td>40</td>
<td>32.41</td>
<td>0.48</td>
</tr>
<tr>
<td>RC</td>
<td>40</td>
<td>33.29</td>
<td>0.45</td>
</tr>
<tr>
<td>TL</td>
<td>40</td>
<td>32.26</td>
<td>0.43</td>
</tr>
<tr>
<td>TH</td>
<td>40</td>
<td>32.95</td>
<td>0.42</td>
</tr>
<tr>
<td>YL</td>
<td>40</td>
<td>36.33</td>
<td>0.48</td>
</tr>
<tr>
<td>YH</td>
<td>40</td>
<td>29.57</td>
<td>0.48</td>
</tr>
<tr>
<td>TLYH*</td>
<td>20</td>
<td>29.43</td>
<td>0.58</td>
</tr>
<tr>
<td>THYL*</td>
<td>20</td>
<td>36.01</td>
<td>0.45</td>
</tr>
<tr>
<td>TLYL*</td>
<td>20</td>
<td>37.15</td>
<td>0.67</td>
</tr>
<tr>
<td>THYH*</td>
<td>20</td>
<td>29.46</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Note. Yarn product samples used in factorial experiment where optical volume was the dependent factor with twist and count as independent factors.

Optical Yarn Diameter Evaluation

The yarn analysis system developed by Lawson-Hemphill is equipped with optical yarn sensors using CCD camera technology with a precision of 0.00325mm. Yarn diameter is measured at intervals of 0.5mm with yarn speed of 100m/min. The system has the capacity to distinguish six different types of yarn defects and generate a summary output of event profiles for the sampled yarn.

Figure 11 illustrates the YAS system used in this study for optical yarn diameter measurements. A yarn transport unit carries the yarn at constant speed and tension across the
measuring zone where the CCD camera scans and records test yarn diameter at lengths based on transport speed. Figure 12 shows yarn diameter profile displayed on the computer screen. The profile illustrates yarn diameter variations along the yarn axis.

Figure 11: Lawson-Hemphill yarn analysis system for yarn diameter.

Picture by David Kurgatt
Figure 12: Diameter profile - Lawson-Hemphill YAS system

Note: The display is an on screen view of yarn profile image together with all settings used to generate the image including yarn length and scanning speed. The vertical scale is in pixels where 1mm is equivalent to 308 pixels.
A summary of optical yarn diameter evaluations for the samples used in this study is provided in Table VIII.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Size</th>
<th>Mean Diameter (mm)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>40</td>
<td>0.276</td>
<td>0.0028</td>
</tr>
<tr>
<td>RA</td>
<td>40</td>
<td>0.257</td>
<td>0.0023</td>
</tr>
<tr>
<td>RC</td>
<td>40</td>
<td>0.266</td>
<td>0.0015</td>
</tr>
<tr>
<td>TL</td>
<td>40</td>
<td>0.271</td>
<td>0.0056</td>
</tr>
<tr>
<td>TH</td>
<td>40</td>
<td>0.257</td>
<td>0.0025</td>
</tr>
<tr>
<td>YL</td>
<td>40</td>
<td>0.275</td>
<td>0.0023</td>
</tr>
<tr>
<td>YH</td>
<td>40</td>
<td>0.246</td>
<td>0.0021</td>
</tr>
<tr>
<td>THYH*</td>
<td>20</td>
<td>0.238</td>
<td>0.0038</td>
</tr>
<tr>
<td>THYL*</td>
<td>20</td>
<td>0.260</td>
<td>0.0016</td>
</tr>
<tr>
<td>TLYL*</td>
<td>20</td>
<td>0.275</td>
<td>0.0027</td>
</tr>
<tr>
<td>TLYH*</td>
<td>20</td>
<td>0.250</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

Note: *Yarn product samples used in factorial experiment where optical volume is the dependent factor and both twist and count as independent factors.
This study adopted various symbols used in calculation of yarn linear density. Descriptions of the symbols and their units are described in Table IX.

Table IX

*Symbols used in Optical Yarn Count Analysis*

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length of yarn scanned for optical diameter (cm)</td>
<td>$L$</td>
</tr>
<tr>
<td>Yarn scan segment length</td>
<td>$l$</td>
</tr>
<tr>
<td>Yarn cut length (cm)</td>
<td>$L_c$</td>
</tr>
<tr>
<td>Scan segment optical diameter (cm)</td>
<td>$d_i$</td>
</tr>
<tr>
<td>Yarn scan segment optical radius = $d_i/2$ (cm)</td>
<td>$r_i$</td>
</tr>
<tr>
<td>Number of scanned segments over yarn cut length $L_c$</td>
<td>$n$</td>
</tr>
<tr>
<td>Number of yarn cut lengths $L_c$ in total length $L$ of yarn scanned</td>
<td>$m$</td>
</tr>
<tr>
<td>Fiber density ($g/cm^3$)</td>
<td>$\rho_f$</td>
</tr>
<tr>
<td>Yarn cut length $L_c$ mass (g)</td>
<td>$w$</td>
</tr>
<tr>
<td>Yarn cut length $L_c$ volume ($cm^3$)</td>
<td>$v_y$</td>
</tr>
<tr>
<td>Nominal yarn count</td>
<td>$t_o$</td>
</tr>
<tr>
<td>Fiber Volume ($cm^3$)</td>
<td>$v_f$</td>
</tr>
<tr>
<td>Fiber volume ratio (FVR)</td>
<td>$\varphi$</td>
</tr>
<tr>
<td>Turns per Centimeter (tpcm)</td>
<td>$t_w$</td>
</tr>
</tbody>
</table>

Optical diameter measuring devices that continuously scan spun yarn cross sectional profile in motion provide opportunities for on-line yarn count analysis. However, in order to
determine yarn linear density from its radius, yarn bulk density or fiber volume fraction is required. Fiber volume to yarn volume ratio is not directly measurable but can be estimated from yarn volume measurements in terms of yarn radius and actual yarn weight. Yarn count analysis based on optical measurements is preceded by a step in which FVR is determined. Fiber distribution curves plotted from normalized radii values and packing densities follow the same curve with yarns spun on similar technologies, with the same twist, count, and fiber parameters (Jiang et al., 2005). Recent research studies on application of yarn diameter focus mainly on yarn defects and objective evaluation of yarn appearance, but not in yarn count analysis. Count measurement and control is a major activity by quality technicians in yarn manufacturing. This research therefore aims to bridge this gap by developing a method based upon optical yarn diameters with a capacity for on-line real time estimation and analysis of yarn linear density. The following assumptions were applied in developing a model for yarn linear density determination based on yarn radius and twist:

- Individual fibers are perfect cylindrical elements randomly distributed within the yarn structure.
- Yarn shape is cylindrical and uniform within individual scan lengths.
- Optical yarn radius is the effective radius of the yarn \( r_1 = \frac{d_i}{2} \).
- Influence of yarn hairiness on yarn diameter is negligible.
- Effect of moisture variation within a controlled environment on sample weight is negligible.

Theoretical Considerations: Yarn Count

Yarn ‘Y’ illustrated in Figure 13 has a nominal yarn count of \( t_o \) (Tex) and nominal yarn twist of \( t_w \) in turns per centimeter and is spun from acrylic fibers of mass density \( \rho_f \) (g/cm³).

If specimen of length \( L_c \) has weight given by \( w \) g, then the fiber volume \( v_f \) contained in \( L_c \) is determined by Equation 2

\[
v_f = \frac{w}{\rho_f} \quad \text{Since} \quad w = v_f \rho_f \quad 1
\]
Figure 13: Simplified pictorial view of spun yarn segments of test specimen “Y”.

Note: Total Length of yarn scanned for optical diameter (cm) = \( L \), Yarn cut segment (cm) = \( L_c \), Yarn scan segment \( S_m \) length (cm) = \( l \) where for \( i = 1, 2, \cdots m \), Segment radius = \( r_i \)

If a sample length \( L_c \) (cm) of yarn is cut and optically scanned for diameter at segments of lengths, \( l_i \) (cm) then the yarn cut length, \( L_c \) is given in Equation 2:

\[ L_c = n \, l. \tag{2} \]

The magnitude of fiber density (\( \rho_f \)) in Equation 1 is inclusive of moisture content due to prevailing ambient conditions. Nominal fiber volume in a skein of a spun yarn “Y” is difficult to obtain due to longitudinal mass variability in spun yarns. Any one of the following three methods may be used to estimate fiber volume in a given length of ring spun yarn:

1. Direct measurements, such as use of a gas pycnometer or fiber density and skein weight
2. Empirical computation using yarn diameter \( d \) as in Equation 3 with a reliable estimate of FVR (El Mogahzy, 1993)

\[ d = -0.10284 + \frac{1.592}{\sqrt{N_e}} \tag{3} \]

3. Estimating optical yarn volume \( v_o \) (cm\(^3\)) from twist (turn/pc) \( t_w \) linear density \( t \) and hence the corresponding fiber volumes \( v_f \). from a product of FVR and optical yarn volume \( v_o \).
Estimation of yarn volume from the firm’s prevailing production parameters will account for the unique fiber and machine properties effects. Empirical computation, however, may fail to capture unique process parameters (twist, fiber, technology, and as forth.). Equation 4 presents the method where yarn optical volume $\mathcal{V}_o$ modeled as a function of yarn twists $t_w$ and yarn count $t$ in Tex. Direct measurement by gas pycnometer was used to verify the estimation of fiber volume from skein weight; initial yarn diameter and fiber blend density from the supplier specification.

\[
\mathcal{V}_o = \beta_0 + \beta_1 t_o + \beta_2 t_w + \beta_3 t_w t_o + \varepsilon \tag{4}
\]

Only one specimen diameter and skein weight was used to compute initial FVR. This method is suitable for checking the accuracy and updating the prevailing FVR. This process will take any changes in the fiber blend parameters into account such as variation in yarn diameter associated with fiber tint or twist changes.

**Estimation of Nominal Optical Yarn Volume OYV**

An estimate of optical yarn volume can be computed using Equation 5. Yarn “Y” scanned for optical diameters in length $L$ (mm) long with a scanning length of $l$ (mm). Twists $t_w$ and yarn linear density $t_o$ are determined from their corresponding yarn lengths $L_c$ as per Equation 2.

\[
\mathcal{V}_o = \hat{\beta}_0 + \hat{\beta}_1 t_w + \hat{\beta}_2 t + \hat{\beta}_3 t_w t \tag{5}
\]

Yarn structure is comprised of fibers and air pockets whose relationship is determined by the spinning technology used. Yarn bulk density is therefore determined by the yarn packing fraction or fiber volume ratio (FVR) defined in Equation 6.

\[
\varphi = \frac{\mathcal{V}_f}{\mathcal{V}_y} \tag{6}
\]

Where $\mathcal{V}_y$ and $\mathcal{V}_f$ are yarn and fiber volumes in a given length of yarn. Packing fraction is an indicator of yarn bulkiness which is constant for a given yarn product. Fiber volume ratio, $\hat{\varphi}$ is estimated as shown in Equation 7 from fiber density and yarn Y specimen weights

\[
\hat{\varphi} = \frac{\mathcal{V}_f}{\mathcal{V}_o} = \frac{\mathcal{W}}{\rho_f \mathcal{V}_o} \tag{7}
\]
By definition, a yarn count \( t \) in Tex units is determined from the weight \( w \) (g) of any yarn length \( L_c \) in Equation 8

\[
t = \frac{10^5 \nu_f \rho_f}{L_c} = \frac{10^5 \varphi V_y \rho_f}{L_c} 
\]

Since \( V_f = \varphi V_y \)

\[\text{Equation 8}\]

Nominal yarn count \( t_o \) (Tex) for yarn \( Y \) given by:\n
\[
t_o = \frac{10^5 \varphi V_y \rho_f}{L_c} = \frac{10^5 w V_y}{V_o L_c} 
\]

\[\text{Equation 9}\]

Estimation of optical volume \( V_y \) for yarn length \( L_c \) with scan segments of length \( r_i \) and optical radii \( r_i \) using Equation 10 assuming cylindrical dimensions as illustrated in Figure 13.

\[
V_y = \pi l \sum_{i=1}^{n} r_i^2 
\]

\[\text{Equation 10}\]

Where \( n = \frac{L_c}{l} \) and hence the nominal yarn count \( t_o \) in Tex units follows:

\[
t_o = \frac{10^5 w \pi l}{V_o L_c} \sum_{i=1}^{n} r_i^2 = \frac{10^5 w \pi}{V_o n} \sum_{i=1}^{n} r_i^2 
\]

\[\text{Equation 12}\]

For adequate sampling of production units from a ring spinning frame, a synchronized multichannel yarn diameter scanning system would be required. Each scanning unit continuously scans yarn for diameter. As illustrated in Figure 13, successive scan lengths of yarn segments \( L_c \) over the total yarn length \( L \) produced during a given production cycle time will be equivalent to \( m \) cut lengths of yarn. Yarn count \( T_{jk} \) for each segment computed in Equation 8 for each successive \( j^{th} \) yarn cut length \( L_c \) from \( k^{th} \) channel of \( C \) channels. Equation 13 gives the mean count \( \bar{T} \) of a spinning machine at time \( t \) immediately after \( S_{jk} \) scanned yarn segments.

\[
\bar{T} = \frac{1}{c \times m} \sum_{k=1}^{c} \sum_{j=1}^{m} T_{jk} 
\]

\[\text{Equation 13}\]

Yarn count values computed between channels are independent due to random roving supply in individual ring frame spindles.

For a given yarn production system, yarn twist, cross-sectional number of fibers and individual fiber crimp jointly influence the resultant yarn radius. FVR \( \varphi \) calculated from fiber volume \( \nu_f \) and yarn optical volume \( \nu_y \) as per Equation 6 since FVR is a function of twist, count,
spinning technology and production parameters (Goswami, Martindale, & Scardino, 1977). FVR is a measure of yarn bulkiness and is a constant for a given family of yarns produced from similar spinning process variables and technology. Fiber volume ratio computed for any yarn length $L_c$ with known radius $r_i$, fiber mass density $\rho_f$ and weight of $w$ (g) is required to compute fiber volume $V_f$ in a given yarn segment and hence, its weight. The OYCA system will therefore require initialized FVR value determined from the prevailing yarn parameters and initial optical yarn radius. For purposes of optical yarn count analysis, estimation of FVR is done from nominal yarn count and twist. Bulkiness is measured in terms of FVR and is a quality characteristic of a given yarn product type. Physical and chemical characteristics of spun yarns are a function of yarn bulkiness. It is therefore imperative that yarn bulkiness in any given yarn product remain constant.

Table X

<table>
<thead>
<tr>
<th>Yarn Code</th>
<th>Ave. Dia. (mm)</th>
<th>Skein Wt. (g)</th>
<th>OYV $V_o$ (cm$^3$)</th>
<th>OFV $V_f$ (cm$^3$)</th>
<th>FVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>0.261</td>
<td>1.8349</td>
<td>2.9353</td>
<td>1.5040</td>
<td>0.5124</td>
</tr>
<tr>
<td>RB</td>
<td>0.278</td>
<td>1.7712</td>
<td>3.3302</td>
<td>1.4518</td>
<td>0.4360</td>
</tr>
<tr>
<td>RC</td>
<td>0.269</td>
<td>1.8527</td>
<td>3.1180</td>
<td>1.5186</td>
<td>0.4870</td>
</tr>
<tr>
<td>YH</td>
<td>0.249</td>
<td>1.5973</td>
<td>2.6716</td>
<td>1.3093</td>
<td>0.4901</td>
</tr>
<tr>
<td>YL</td>
<td>0.275</td>
<td>1.9336</td>
<td>3.2587</td>
<td>1.5849</td>
<td>0.4864</td>
</tr>
<tr>
<td>TH</td>
<td>0.262</td>
<td>1.8565</td>
<td>2.9579</td>
<td>1.5217</td>
<td>0.5145</td>
</tr>
<tr>
<td>TL</td>
<td>0.272</td>
<td>1.7573</td>
<td>3.1880</td>
<td>1.4404</td>
<td>0.4518</td>
</tr>
<tr>
<td>THYL</td>
<td>0.261</td>
<td>1.9486</td>
<td>2.9353</td>
<td>1.5972</td>
<td>0.5441</td>
</tr>
<tr>
<td>TLYL</td>
<td>0.278</td>
<td>2.0583</td>
<td>3.3302</td>
<td>1.6871</td>
<td>0.5066</td>
</tr>
<tr>
<td>TLYH</td>
<td>0.251</td>
<td>1.6293</td>
<td>2.7147</td>
<td>1.3355</td>
<td>0.4919</td>
</tr>
</tbody>
</table>

Note: Fiber density based on pycnometer test = 1.22 g/cm$^3$
Evaluation of Yarn twist

Yarn twist measure was conducted according to ASTM D1422 - 99(2008) Standard Test Method for Twist in Single Spun Yarns. This method employs the principle of untwist-retwist where the assumption is that twice as much twist will be required to twist and re-twist the yarn to the original tension. Random 20-inch yarn specimens from each cone were tested for twist with two replications using Zweigle D314 and ILE automatic twist testers. Table XI presents a summary of twist tests results obtained in this study.

Table XI

Summary of Yarn Twist Test Results

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Size</th>
<th>Mean count</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>40</td>
<td>12.46</td>
<td>0.41</td>
</tr>
<tr>
<td>RA*</td>
<td>40</td>
<td>12.49</td>
<td>0.51</td>
</tr>
<tr>
<td>RC</td>
<td>40</td>
<td>12.48</td>
<td>0.45</td>
</tr>
<tr>
<td>TL</td>
<td>40</td>
<td>11.2</td>
<td>0.42</td>
</tr>
<tr>
<td>TH</td>
<td>40</td>
<td>13.06</td>
<td>0.53</td>
</tr>
<tr>
<td>YL</td>
<td>40</td>
<td>12.26</td>
<td>0.53</td>
</tr>
<tr>
<td>YH</td>
<td>40</td>
<td>12.45</td>
<td>0.55</td>
</tr>
<tr>
<td>TLYH*</td>
<td>10</td>
<td>10.96</td>
<td>0.43</td>
</tr>
<tr>
<td>THYL*</td>
<td>10</td>
<td>13.58</td>
<td>0.55</td>
</tr>
<tr>
<td>TLYL*</td>
<td>10</td>
<td>11.06</td>
<td>0.42</td>
</tr>
<tr>
<td>THYH*</td>
<td>10</td>
<td>13.60</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Note: *Yarn product samples used in factorial experiment with optical volume as dependent factor with twist and count as independent factors.
Fiber Volume Ratio

During the final spinning stage of 100% acrylic ring spun yarn production, a final mass of fibers delivered by the front drafting roll continuously spiral around the yarn axis due to constant twist action by ring, spindle and traveler system. Twist acts to bind groups of fibers together into a continuous strand of yarn. The ensuing yarn linear weight and twist variation is subject to mechanical instability in spinning systems and lack of uniformity in raw materials. The uniformity of a cross-sectional mass of fibers and the level of twist in spun yarns are subject to the type of spinning technology which in turn affects yarn specific volume. Micromeritics AccuPyc II 1340 gas pycnometer was used in this study to evaluate the FVR of yarn specimens. A 10cm$^3$ capacity sample chamber was selected in order to accommodate the 60 yards of 18/1 acrylic yarn. Pycnometric test results were used to verify data on skein fiber volumes computed from average optical skein diameter. Ten sample skeins were randomly selected from the main sample of 40 part cones and both replicate skeins were included to make a total of 20 specimens. In the case where the main sample size was only 10 part cones, all were included in the pycnometric tests. Over 20 minutes is required to run one skein volume test with five purges and five cycles. In order to conduct all the tests at the allotted pycnometer time, five purges and five cycles were used in less than 10% of the total volume test runs. Figure 14 is a picture of Micromeritics' new AccuPyc II 1340 instrument used in this study. Ultra pure helium gas was used in the set-up, based upon the recommendations of the manufacturer. Options available before sample runs are the number of cycles, purges and type of report. AccuPyc II 1340 provides an option for density/volume report or volume only report. If density is required then sample mass is directly keyed through the balance system or via an external USB keyboard or key pad. A standard AccuPyc II 1340 report for density/volume is illustrated in Figure 14.
Figure 14: Micromeritics AccuPyc II 1340 with 10 cm$^3$ sample chamber.

Picture by D. Kurgatt

Note: The sample holder is inserted into a chamber receptacle once the specimen is fully packed into the holder. The chamber is then sealed using a locking cap. A keypad or USB keyboard interface command is required to start sample analysis. Inset photo is a 6.370621cm$^3$ standard calibration steel balls.
Figure 15: AccuPyc II 1340 volume/density report sample RB09A

Note: For this study, only skein volume measurement is required. Density was computed directly using skein mass obtained for yarn count tests since the same skeins were used. The report is showing the average volume and density of specimen RB09A.
CHAPTER 4

RESULTS AND DISCUSSION

The purpose of this study was to develop a methodology for analysis and control of spun yarn count from optical diameter measurements in production. The system was based on an empirical relationship between yarn cross-sectional diameters and yarn count. Samples were randomly drawn from 100% acrylic ring spun yarns from three spinning plants using the same installed spinning equipment. Yarns were sampled from standard production that meet the firm’s production requirements followed by a combination of count and twist parameters randomly adjusted to ±10% levels to allow for a comparative evaluation of both the OYCA and ASTM 1907 test methods. A total of seven yarn product samples were coded (TL, TH, YL, YH, THYL, TLYH, TLYL, and THYH) and were produced by adjusting spinning twist and count parameters to ±10% that of the prevailing firm’s spinning parameters. In addition, three yarn product samples were drawn from the standard production in each constituent spinning plant and coded RA, RB, and RC respectively. Each yarn product sample was treated as an independent sample. Hypotheses for this study were developed based on structural properties of spun yarns shown by research findings to be a function of yarn count. The ASTM D 1907-89 test method was used in this study as a reference test method for yarn count.

Yarn Testing

Optical yarn diameter and gas pycnometer testing equipment used in this research study could not be located in one laboratory due to ownership restrictions. Therefore, sample testing in this study was conducted in four different locations and times, in order to accommodate for available equipment, and participating plant opportunity to carry out necessary changes for sample production. Ambient temperature conditions maintained by the textile firms and yarn testing laboratories in the three locations where skein sampling, twist testing and optical diameter scanning were conducted and maintained at the existing environmental conditions (70 ± 2°F and 60% ± 2%RH). Any fluctuations on these conditions reflected prevailing ambient conditions in yarn spinning plants. Gas pycnometer volume testing is very sensitive to fluctuations in the
ambient temperature. During pycnometry testing, ambient conditions were therefore controlled at 60±2% RH and 70.3 ±2% °F.

**Research Questions and Hypotheses**

To establish the relationship of optical yarn diameter to yarn count, tests were performed to explore the association of optical yarn volume (OYV) with yarn twist and yarn count in 100% ring spun acrylic yarns produced from the same spinning technology and fiber blend at different twist and count levels within ±10%. Optical yarn volume for the yarn specimens were computed from optical yarn diameters of individual yarn skein specimens. To extensively explore the efficacy and validity of the OYCA test method, this study evaluated method agreement in test samples that were produced from different plants running the same technology and production parameters across different acrylic fiber blends, color, twist and count up to ±10% levels. Significance in the association was evaluated at p ≤ 0.05.

**Research Question One**

Is there any relationship among OYV, yarn twist and yarn count in 100% ring spun acrylic yarns?

**Implication of Research Question One**

Statistical implication of question one shows that there is a meaningful relationship between optical yarn volume, yarn twist and yarn count. In spun yarn spinning operations, twist and yarn fiber mass (represented as yarn linear density) are two key quality parameters used for yarn count control and their relationship to OYV will provide the potential to exercise control from optical scan diameters.

**Research Hypothesis One**

There is no relationship among OYV ($V_y$), yarn twist and yarn count in selected 100% acrylic yarns.
Implication of Hypothesis One

Any relationship detected among OYV ($V_f$), yarn twist and yarn count in selected 100% acrylic spun yarns is only due to measurement errors associated to sampling, equipment or raw materials.

Research Question Two

Is there any relationship between fiber specimen volumes $V_f$ obtained by constant volume gas pycnometer test method and yarn OYV ($V_y$) from the same yarn specimens?

Implication of Research Question Two

The statistical implication of Research Question Two is that since only fiber mass in yarn specimens account for the linear mass density, fiber volume has no relationship with OYV and that other factors influenced the magnitude of OYV.

Research Hypothesis Two

There is no relationship between fiber volumes ($V_f$) by constant volume gas pycnometer test method with OYV.

Implication of Research Hypothesis Two

Any relationship detected between fiber volume ($V_f$) and OYV is solely due to chance and that other factors may act individually or in concert to influence the magnitude of OYV.

Research Question Three

Do changes in yarn twist and yarn count within ±10% levels in 100% acrylic ring spun yarns produced on the same spinning technologies and fiber blends affect OYCA count computation from OYV?
Implication of Research Question Three

Effective application of OYCA test method across different yarn products is dependent upon significant a functional relationship between OYV and key yarn parameters namely; twist and yarn linear density (measure of fiber mass in a textile strand).

Research Hypothesis Three

Yarn count and twist changes within the production range of ±10% levels do not have any significant effect on OYV measurements in selected 100% acrylic yarns produced in the same spinning technologies, fiber blend and process specifications.

Implication of Research Hypothesis Three

The OYCA principle is based on the hypothesis that OYV has a functional relationship with yarn twist and linear density within a given fiber blend and spinning technology. If OYV is not predictable from twist and yarn count, the OYCA method will therefore not offer any effective measure of yarn count in spun yarn products.

Research Question Four

Is there any significant difference between the OYCA and ASTM D 1907-89 test methods among the three independent plants producing 100% acrylic ring spun yarns on the same spinning technology, fiber blend and process specifications?

Implication of Research Question Four

The proposed OYCA method did not differ in count measurements when compared to ASTM D 1907-89 on the same yarn population from independent and remote spinning plants producing 100% acrylic ring spun yarns on the same spinning technology, fiber blend and process specifications.
**Research Hypothesis Four**

The difference between (OYCA) and ASTM D-1907-89 test methods in determining yarn linear density in selected 100% acrylic yarns does not differ significantly among spinning plants operating the same spinning technologies, fiber blend and process specifications.

**Implication of Research Question Four**

The difference between yarn count test results by OYCA and ASTM D-1907-89 methods should not differ significantly between spinning plants with similar spinning technology and a process designed for a particular spun yarn product. OYCA results should be comparable between remote and independent plants.

**Research Question Five**

Is there any agreement between OYCA and ASTM D 1907 test methods over the ±10% level changes in twist and yarn count in 100% acrylic ring spun yarns produced on the same spinning technology and fiber blend?

**Implication of Research Question Five**

Correlation coefficient is an indication of strength in the relationship between the two variables. Correlation alone does not measure the extent of agreement between two test methods (Altman, and Bland, 1983). There is no agreement between OYCA and ASTM D 1907- 89 due to a functional relationship of yarn count variance, and its mean or magnitude of count measure and reproducibility of test results under different yarn physical conditions.

**Research Hypothesis Five**

There is no agreement between OYCA and ASTM D1907-89 test methods in determining yarn linear density of the selected 100% acrylic yarn between plants running similar spinning technologies, fiber blend and process specifications.
Implication of Research Hypothesis Five

OYCA has no significant agreement with ASTM D-1907-89, which is an established method for process control and commercial exchange application in spun yarn products. Advantages offered by a quick, on-line and remote control of yarn count opportunities can only be exploited if OYCA and ASTM D1907-89 test methods have significant agreement in test results for yarn count of the selected 100% acrylic yarn between plants running similar spinning technologies, fiber blend and process specifications.

Research Design and Data Analysis

The purpose of this study was to determine whether or not OYCA methodology based on well known spun yarn structural properties that relate to yarn twist and diameter will significantly agree with ASTM D-1907-89 test method for yarn count in spun yarns. It is imperative to note that yarn diameter measurements obtained by different techniques produce differing results. Jaouadi, Msahli and Sakli (2009) noted that the empirical formula developed by El Mohgazy (1993) returns higher yarn diameter values than those estimated by equations developed by Peirce (1937). Therefore, research questions and tests formulated for this study were used to test the computational methodology of yarn count from optical yarn diameters and fiber volume ratios computed from optical yarn volume, which is expected to differ from FVR computed based on real yarn envelope volume or that computed from microscopic yarn diameter.

Sample size and power of the statistical tests were computed from mill historical data of yarn count CV% for a paired t-test using Minitab 15. Test of associations and functional relationships between optical yarn volume and yarn properties were carried out using Statistical Package for the Social Sciences (SPSS). Data collection was further designed to provide spinning plant, count test method, blend color, twist and count levels, as independent variables where yarn count from both OYCA and STM methods including OYV and skein fiber volumes were the dependent variables. Method comparison was carried out using Altman-Bland Test available in Analyse-it V2.21 extension in Microsoft Excel 2007. Method comparison requires replicated test data to determine repeatability measures. For purposes of repeatability, two replications of count for each test method were conducted.
Power and Sample Size

The following factors limited availability of gas pycnometer test time; length of time the equipment was on loan for the study, test and equipment delivery time to the Retail Merchandising and Product Development textile laboratory at Florida State University. Only 10 specimens with two replications were possible for skein volume tests. This sample size was considered adequate for verification of computed fiber volumes by OYCA method. Five different yarn sample types at two count levels and two twist levels, including a combined twist and count at the standard levels were used in method comparison. Count and twist level were adjusted to ±10% of the prevailing production level. By drawing 20 specimens from each sample type, 100 specimens with one replicate were obtained. A paired t-test is equivalent to 1-t test (N=100) by Minitab 15 computation gave Power=0.98, p<.05. A 2-level factorial analysis with (N=10) replicates gave power >.99, p<.05.

Objective 1

To explore the relationship of OYV with twist and count in 100% spun acrylic yarns, a sample of 20 specimens with two replicates from each yarn product was randomly drawn, evaluated and results used to explore the relationship of OYV with twist and count. All specimens were evaluated for optical yarn diameter and only one replicate was used in bivariate correlation analysis. Twist tests were conducted on each specimen without replication. Table XIII shows the summary statistics of OYV, yarn twists and count.
Table XII

*Descriptive Summary: Count, Twist, and OYV*

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn Twist (tpi)</td>
<td>219</td>
<td>12.33</td>
<td>1.00</td>
<td>-0.04</td>
</tr>
<tr>
<td>Optical Yarn Volume (OYV)</td>
<td>219</td>
<td>2.95</td>
<td>0.29</td>
<td>-0.17</td>
</tr>
<tr>
<td>Yarn Count</td>
<td>219</td>
<td>32.81</td>
<td>2.70</td>
<td>0.22</td>
</tr>
</tbody>
</table>

All yarn variable parameter test data were examined for normality and no violation was observed. A bivariate analysis of correlation was carried out and a summary of the results presented in Table XIII. A large positive correlation, $r (219) = 0.67$, $p < .001$ was observed between OYV and Yarn Count. A medium negative correlation, $r (219) = -0.3$, $p < .001$ between Yarn Twist and OYV was observed. An increase in twist, according to the observation correlation, will lead to a decrease in OYV but an increase in OYV at a constant twist will lead to an increase in yarn count. The observed correlations of ($r = 0.67$) and ($r = 0.35$) are large and medium effect sizes (Cohen, 1988).
Table XIII
Correlation Coefficients Between OYV*, Twist and Count

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Yarn Twist (tpi)</th>
<th>Optical Yarn Volume (OYV)</th>
<th>Yarn Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn Twist (tpi) Pearson Correlation</td>
<td>1</td>
<td>-0.35**</td>
<td>-0.06</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.000</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Optical Yarn Volume (OYV) Pearson Correlation</td>
<td>1</td>
<td>0.67**</td>
<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yarn Count† Pearson Correlation</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).
†Yarn count tested according to ASTM D-1907-89

Objective 2

To study the relationship of OYV and skein fiber volume ($V_f$), measurements of skein fiber volumes were carried out using a gas pycnometer running on high purity helium gas. A random selection of 10 paired skein samples were drawn from all eleven yarn sample categories. Each skein specimen was tested for fiber volume with three pycnometer purges and cycles instead of five purges recommended by the manufacturer to ensure a sufficient number of samples. A graphical exploration of the relationship between OYV and fiber volume was conducted and a line plot is shown in Figure 16. Spearman’s correlation coefficient was determined between OYV and fiber volume. The bivariate correlation results are shown in Table XIV. A large positive Spearman’s correlation $r (60) = 0.96$, $p<.01$ reflects a strong relationship between OYV and fiber volume. These results suggest that only 96% of OYV can be explained by fiber volume in the absence of twist and its interactions with yarn count.
Figure 16: Plot of optical yarn volume (OYV) with pycnometer fiber volume.

Table XIV
Correlation Coefficients between OYV* and Fiber Volume (Pycnometer)

<table>
<thead>
<tr>
<th></th>
<th>Optical Yarn Volume (OYV)</th>
<th>Pycnometer Fiber Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Yarn Volume</td>
<td>Pearson Correlation</td>
<td>1</td>
</tr>
<tr>
<td>(OYV)</td>
<td>Sig. (2-tailed)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>60</td>
</tr>
<tr>
<td>Pycnometer Fiber Volume</td>
<td>Pearson Correlation</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>60</td>
</tr>
</tbody>
</table>

**. Correlation is significant at the 0.01 level (2-tailed).
Objective 3

Identification of different yarn products is based on count, twist appearance, spinning technology, fiber content and count. Yarn products in the same family of fiber blends and technology are identified based on their twist and count levels. High explanatory powers from yarn twist and yarn count factors of OYV are therefore essential for the validity in OYCA method over a wider range of yarn products spun on the same fiber blend and technology. Factorial designs offer higher relative efficiency advantages compared to one-factor-at-time designs (Montgomery, 2005). A two-factor two-level factorial design with center points was adopted for this study for an independent estimate of error and a check on linearity assumptions. A $2^2$ factorial design with 10 replicates on each corner point, augmented by 10 replicates at the center point was used in the study. The design and factor coding used in *Minitab* 15 to run the factorial experiment is shown in Figure 17. Production of yarn samples at all factor levels was completed in one spinning plant with the capacity to provide the same color and fiber blend at all factor levels.

![Factorial design in Minitab 15](image)

Figure 17: $2^2$ Factorial design augmented with center points in *Minitab* 15
Factorial analysis was run on *Minitab 15*. Beta coefficients for main effects, constant and first order interaction terms were all significant. OYV is therefore estimated by $OYV = 2.85 - 0.17*\text{Twist} + 0.26*\text{Count} - 0.04*\text{Twist}*\text{Count}$. Results of curvature ($p = 0.83$) was not significant. The adjusted $R^2$ value for the factorial model was 0.95, which is a large explanation power. ANOVA analysis for the factor effects are shown in Table XV. Graphical evaluation and demonstration of model adequacy plots are shown in Appendix B.

### Table XV

*Analysis of Variance of Factor Effects in OYV versus Twist, and Count*

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>ss</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>2</td>
<td>3.84</td>
<td>1.91</td>
<td>485.92</td>
<td>0.000</td>
</tr>
<tr>
<td>2-Way Interactions</td>
<td>1</td>
<td>0.05</td>
<td>0.05</td>
<td>12.79</td>
<td>0.001</td>
</tr>
<tr>
<td>Curvature</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.83</td>
</tr>
</tbody>
</table>

### Objective 4

Due to significant increase in global textile interactions between vendors and manufacturers of textile products, standardization of quality analysis and test methods have become very important. Textile firms operate different plants in different locations within the United States or globally. It is therefore imperative that a test method for any quality aspect be performed in the same way regardless of location or product. To guard against false spun yarn count differences among spinning plants, the two methods were paired and since the tests were conducted on the same specimens, any differences should reflect the bias between OYCA and ASTM D-1907-89 test methods. Table XVI shows the descriptive of count differences among the spinning plants. A one-way ANOVA was run on different methods among the spinning plants and the results are presented in Table XVII. There was no significant statistical difference
found among the three spinning plants on count differences between method, \( F (2,114) = 1.39, p = .254 \). This was an indication that from the OYCA and ASTM methods were consisted across spinning plants.

Table XVI

*Descriptive Statistics for Method Differences Among Spinning Plants*

<table>
<thead>
<tr>
<th>Spinning Plant</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burlington</td>
<td>39</td>
<td>-0.056</td>
<td>0.625</td>
<td>0.100</td>
<td></td>
<td>-0.259</td>
<td>0.146</td>
</tr>
<tr>
<td>Norlina</td>
<td>39</td>
<td>-0.250</td>
<td>0.712</td>
<td>0.114</td>
<td></td>
<td>-0.481</td>
<td>-0.020</td>
</tr>
<tr>
<td>Anderson</td>
<td>39</td>
<td>-0.273</td>
<td>0.546</td>
<td>0.088</td>
<td></td>
<td>-0.450</td>
<td>-0.096</td>
</tr>
<tr>
<td>Total</td>
<td>117</td>
<td>-0.193</td>
<td>0.634</td>
<td>0.059</td>
<td></td>
<td>-0.309</td>
<td>-0.077</td>
</tr>
</tbody>
</table>

Table XVII

*Analysis of Variance of Method Differences Among Spinning Plants*

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>1.106</td>
<td>2</td>
<td>0.553</td>
<td>1.387</td>
<td>0.254</td>
</tr>
<tr>
<td>Within Groups</td>
<td>45.443</td>
<td>114</td>
<td>0.399</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>46.549</td>
<td>116</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Objective 5**

In industry, comparison of two or more measurement techniques may become necessary for commercial exchange of products, or the need for product quality improvement and cost
reduction. McCullough, Kwon and Shim (2003) compared five standard methods used in measurement of water vapor transmission through textile fabrics designed for use in outdoor garment production by using Spearman rank order correlation. Witkowska and Fydrych (2005) used Kendal’s agreement coefficient to compare six test methods under ISO standards used in measurement of fabric tear resistance. Method comparison based on correlations are not appropriate and misleading since they fail to take into account the lack of method agreement even with high correlation effects (Altman and Bland, 1986). Methods or techniques that simultaneously employ correlation and graphical assessments are better suited to method comparison. The objective of this study was to compare OYCA and The ASTM D-1907 yarn count test methods in 100% ring spun acrylic yarns produced on the same spinning technology with the same fiber blend and process specifications under the following conditions:

a. Different twist levels within ±10% of nominal twist.

b. Different yarn count levels within ±10% of nominal count.

Test of agreement or method comparison chosen for this study was designed by Altman-Bland in Analyse-it MS Excel (Analyse-it Software Ltd, 2009), and provides the following factors and plots applied together in computing repeatability coefficient, correlation coefficient of differences and mean of test method. Bias measurements, scatter plots for methods repeatability, and difference are other factors used in determination of sufficiency in method agreement. Statistical data output from Analyse-it MS Excel for method agreement is shown in Figures 18. Low correlation ($r =0.02$) effect (Cohen, 1988) between absolute differences and average of OYCA and ASTM D 1907 observed was an indication of constant bias.
Association

A significant linear relationship between two test methods is an indication of possible method agreement. To explore the association OYCA test method with ASTM 1907-89 test method over ±10% levels change in yarn count. A bivariate correlation analysis was carried out on RA yarn which was from one fiber tint at standard twist. Change in stock linear density is a regular issue that spun yarn firms have to contend with more frequently than twist variation issues. In this study RA yarn samples were produced from natural fiber blend and count was
varied to obtain samples of ±10% yarn count levels. An exploration of count data did not indicate any violation of normality and therefore Pearson correlation coefficient was computed. A significant correlation, $r (60) = 0.96$, $p < .01$ between OYCA and ASTM test methods was observed. The correlation test was run on one replicate of each count test method in the Altman-Bland method agreement; results produced significant correlation effects $r (200) = 0.90$, $p < .01$. The observed correlations are large effects (Cohen, 1988) which provide strong indication of sufficient method agreement. Figure 19 provides a visual assessment by Altman-Bland agreement method for the OYCA and ASTM1907-89 test methods.

Figure 19: Altman-Bland plot of OYCA against ASTM 1907-89 test method.

**Limits of agreement**

Sufficient agreement is estimated by the mean differences of the two methods when no relationship is observed between the differences and mean of the two methods under evaluation. Altman-Bland plot of differences between the means of the OYCA and ASTM test method is illustrated in Figure 20, showing the relationship between the differences and magnitude of mean
counts. The dotted lines shown in Figure 19 indicate the limits of agreement between OYCA and ASTM 1907 test methods.

![Altman-Bland plot of OYCA and ASTM differences against means.](image)

Figure 20: Altman-Bland plot of OYCA and ASTM differences against means.

**Agreement**

The bias estimated by mean difference \( \bar{d} \) shown was consistent and significant \( t(100) = -7.40, p < .001, d = -0.55 \). Subtraction of the bias from mean of the new method will bring the results closer if not equal to identity. These results therefore indicate statistically significant agreement with ASTM. Beside the consistency in bias, the difference did not exceed 3% of yarn count mean and was within the limits of spun yarn count. Human eye can detect variations of 2% in mean spun yarn number in plain faced fabrics with 100% cover (Uster, 2005). Fiber volume
ratio of individual yarn products used in this study were estimated once from a single skein weight and average optical skein volume. The value of FVR in a production system does not have a particular measure of FVR but is random and at best estimated by a sample mean value. The FVR value of RA yarn product specimens used in OYCA was estimated from one skein specimen with FVR=0.512. A t test against pycnometer measured FVR values for RA yarn specimens were not significantly different, t (19) = -1.75, p = .10, d = .005. According Cohen’s (1988) guidelines this effect is small. Variability of FVR values in a given yarn product specimen is illustrated in Figure 21 by using pycnometer measured skein fiber volumes \( v_f \) and optical diameters. Accuracy of OYCA results is dependent on the validity and accuracy of FVR values. It is important to validate values of FVR used in OYCA computation periodically.

Figure 21: Plot of FVR values of RA yarn specimens with a reference mean line.
Repeatability

Assessment of repeatability of OYCA test method carried out using replicated measurements did not reveal any association between the mean and standard deviation. A plot of standard deviation against the mean is illustrated in Figure 22 indicates lack of association between the mean and within subject standard deviation. A significant small effect in correlation coefficient \( r (100) =0.02, \ p<.01, \) indicates that 95% repeatability coefficient of 2.15 was higher in the OYCA when compared to 1.4 for ASTM D 1907. The higher repeatability coefficient in OYCA is attributed the nature and method used in optical diameter measurements namely; camera configuration, shape factor, yarn hairiness or tint in component fiber blend. Computation of skein optical volume assumes perfect cylindrical shape and the variations thereof will factor into the overall computed OYC based on optical volume. Based on standard deviations of replicates, the OYCA method is shown by the study to be significantly repeatable over the range of yarn count and twist levels used in this study.

Figure 22: Repeatability plot of OYCA count test method.
CHAPTER 5

SUMMARY AND CONCLUSIONS

The purpose of this study was to develop an empirical methodology for yarn count control and analysis by using optical diameter measurements of dynamic spun sections. Achievements of significant development in instrumentation and sensor technologies have paved the way for the development of new technologies in product testing and process control. Peters (2003) classified yarn count testing among off-line yarn quality evaluation methods. Results of this study along with the latest state of the art optical sensor technology should pave the way for further research and evaluation of new on-line systems in yarn quality engineering and process control.

Objectives of this study were formulated to investigate the relationships and interactions of various yarn quality parameters to yarn linear density based on previous research studies on structural and physical properties of spun yarns. In order to use optical diameters, the relationship between optical yarn volumes and yarn count were explored. Optical yarn count (OYC) was defined in this study as a yarn count computed from optical diameters of longitudinal yarn segments and pre-determined yarn optical fiber volume ratio distinguished from cut-and-weigh count measurements by ASTM 1907-89 method.

The objectives developed and studied in this study progressively followed the relationship between yarn structural properties and yarn optical parameters. These objectives were to:

1. Explore the association of optical yarn volume (OYV) with yarn twist and yarn count in 100% ring spun acrylic yarns produced from the same spinning technology and fiber blend at different twist and count levels within ±10% levels.
2. Explore the association of OYV of 100% ring spun acrylic yarns at different twist and yarn count levels with fiber volume ($V_f$) by constant-volume gas pycnometry.
3. Determine the impact of different twist and yarn count levels on OYV in 100% ring spun acrylic yarns spun on the same spinning technologies, fiber blend and process specifications.
4. Explore the difference between OYCA and ASTM D 1907-89 test methods in 100% ring spun acrylic yarns between spinning plants running on the same spinning technology, fiber blend and process specifications.

5. Compare OYCA and the ASTM D-1907 yarn count test methods in 100% ring spun acrylic yarns from different spinning plants running the same spinning technology, fiber blend and process specifications under the following conditions:
   i. Different twist levels within ±10% of nominal twist.
   ii. Different yarn count levels within ±10% of nominal count.

6. Develop recommendations for on-line yarn linear density analysis and control of spun yarns production based on the OYCA methodology.

Experimental laboratory studies were conducted on yarns sampled across three spun yarn spinning plants operated by one firm. These plants equipped with state of the art spinning technologies are located in different cities. Optical yarn diameter measurement, skein sampling and twist testing were carried out in Clemson University in the Department of Material Sciences. Fiber volume measurement using a gas pycnometer was carried out at Florida State University in the Department of Retail Merchandising and Product development. Altman-Bland test for method agreement, bivariate correlation, one-way ANOVA, and factorial data analysis were used in this study.

Summary of Findings

Correlation effect \( r (219) = .67, p < .01 \), between optical yarn volume and yarn count measured using ASTM D 1907 - 89 was significant. Yarn twist had significant negative correlation effect \( r (219) = -.35, p < .01 \) which supported existing literature findings that show an a decrease in yarn diameter with increasing yarn twist up to a maximum value upon which inter-fiber movement is no longer possible due to lack of space. Further twisting beyond this point will build up stresses within internal fiber structure. Yarn linear density is a representation of the actual mass of fiber distributed longitudinally within the entire length of a given yarn specimen. OYV was found to be significantly correlated, \( r (60) = .96, p < .01 \) which indicated that 96% of OYV could be explained by fiber volume.
A factorial experimental design for prediction of OYV from twist and yarn count had significant main and interaction effects, $OYV = 2.85 - 0.17^{*}Twist + 0.26^{*}Count - 0.04^{*}Twist^{*}Count$. This findings show that OYV has a functional relationship with key yarn structural parameters and since OYC is directly estimable from OYV, OYCA method of count test can be used in count analysis across yarn products of different yield and twist levels. Analysis of variance of count difference between independent yarn spinning plants was not significant. The results indicated that OYCA method can be applied in different manufacturing plants without adverse effect on the constancy of method bias.

Altman-Bland (1986) test method for agreement is widely applied to test agreement and sufficiency between two methods for purposes of method substitution or adoption of new measurement technique against established and reliable method. A number of research studies use correlation effects as sufficient indication of agreement between two test method which is regarded inadequate misleading cases where a large effect in correlation exist but methods still fail to significantly agree for practical application (Bland and Altman, 1986). Altman-Bland agreement test was chosen as a capstone statistical test for this study specifically because the main objective of the study was to test a new method against an established method for agreement.

The results of Altman-Bland test indicated sufficient agreement between OYCA and ASTM D 1907-89 test methods for spun yarn count. Consistency in bias, high correlation and repeatability within the new method in addition to a functional relationship between OYV with yarn twist and count support the sufficiency finding of OYCA method in comparison the established cut-and-weigh off-line count testing by ASTM D 1907-89 standards.

**Conclusion**

Factors manipulated and studied in this research study have provided sufficient evidence to support the proposed on-line yarn count analysis using OYCA system. The study findings show evidence of significant effects of relationship between yarn optical parameters optical yarn volume (OYV), optical fiber volume ratio (FVR) and yarn count. The study has further demonstrated sufficient agreement between methods by analysis on variance demonstrated the capacity OYCA to be used in different plants, which employ similar technology and fiber blend parameters. This study concludes thus that there exist real and practical opportunity of applying
optical scanning and sensing technology to on-line analysis of yarn count. The latest generation of yarn diameter testing machines running on software with exportable data, archival and networking capacities under a windows environment.

**Implications and Recommendations**

On-line methods provide significant opportunities for cost savings and quality improvement. Latest optical scanners are robust to ambient conditions within the production environment, have lower maintenance, consistent and accurate test data transmitted in real time to central computing units for analysis and possible machine actuation. Modern spinning plants are equipped with digital variable speed drive systems controlled from a central computer or individual computing stations on each machine on the production floor.

The study was conducted using 100% ring spun acrylic yarns and it is recommended that evaluation on different fiber blendes such as cotton or synthetic fiber blendes or different spun yarn technologies need to be evaluated before adopting the system. EIB Lawson-Hemphill system equipped with one CCD camera was used in this study. Yarn diameter and hairiness test systems with dual scanning technology are available in the market, which claims capacity to evaluate yarn shape factor. Yarn hairiness and production speeds are other criteria likely to have an impact on the results of yarn diameter measurements. During analysis of the results in this study it was noted that different yarn colors differed significantly on optical yarn diameter values. Since the camera system used relies on transmitted light to gauge the size of a running yarn diameter it was observed that natural yarn differed significantly in diameter from black tinted yarn. This phenomenon was attributed to the impact of transmitted light through the yarn structure. In addition to fiber tint, variation in physical properties among different color ways in fiber groups including yarn hairiness are all expected to have some form of influence on transmitted light flux through yarn structure. It is recommended that future studies look further into this factor within and across different camera system and various fiber tints. These factors did not however impact OYCA system since the estimated initial fiber volume ratio was based on real fiber weight of a sample specimen, i.e. individual fiber volume ratios were used in each yarn product studied.
APPENDIX A

Copyright Permission Letters

October 20, 2010

David K. Kurzatt
2375 Eagle Glen Ct.
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USA

To,

Paul A. Webb
Micromeritics Instrument Corporation
4356 Communications Drive
Norcross, GA 30093-2901,

Dear Dr. Webb,

This letter will confirm our recent e-mail correspondence. I am completing a doctoral dissertation at Florida State University entitled “Optical Yarn Diameter: On-line Control and Count Analysis in Spun Yarns”. I would like your permission to reprint in my dissertation an adaptation from the following:


The excerpts to be reproduced are adapted illustration of gas pycnometer working principle. A copy of the contents from the manuscript is enclosed.

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If these arrangements meet with your approval, please sign this letter where indicated below and return it to me by post.

Thank you very much.

Sincerely,

David K. Kurzatt

PERMISSION GRANTED FOR THE USE REQUESTED ABOVE

[Signature]

Dr. Paul Webb

Micromeritics Instrument Corporation

Date: 10/22/10
October 1, 2010

David K. Kurgatt
2375 Eagle Glen Ct.
Canton, NC 28105-7985
USA

To,

Edith Aepli
Senior Manager Marketing & Communication
Uster Technologies AG, Sonnenbergstrasse 10
CH - 8610 Uster / Switzerland

Dear Edith,

This letter will confirm our recent e-mail correspondence. I am completing a doctoral dissertation at Florida State University entitled "Optical Yarn Diameter: On-line Control and Count Analysis in Spun Yarns®. I would like your permission to reprint in my dissertation an adaptation from the following:


The excerpts to be reproduced are adapted illustration in Figure 3 of opto-electronic sensor OM, Table II of Yarn quality Characteristics by Uster® Yarn Standards and a description of Yarn Tensile Quality Characteristics by Uster® Yarn Standards in Table III. Copies of content described above are enclosed for your information and review. The requested permission extends to any future revisions and editions of my dissertation, including non-exclusive world rights in all languages, and to the prospective publication of my dissertation by UMI Company. These rights will in no way restrict republication of the material in any other form by you or by others authorized by you. Your signing of this letter will also confirm that Uster Technologies AG owns the copyright to the above-described material. If these arrangements meet with your approval, please sign this letter where indicated below and return it to me by mail.

Thank you very much.

Sincerely,

David K. Kurgatt

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[Signature]

Date: 10.07.10

Edith Aepli
Uster Technologies AG
Sonnenbergstr. 10
CH-8610 Uster

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Graphical Evaluation of Factorial Analysis

Figure A 1: Normal and half-normal plots of factorial analysis
Figure A 2: Plots of residuals versus OYV and fitted values of factorial analysis.
REFERENCES


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BIOGRAPHICAL SKETCH

David K. Kurgatt

EDUCATION

Ph.D.  
*Florida State University, Tallahassee, FL, USA*

**Ph.D. Candidate**

Major: Textiles  
Focus: Textile Product Development  
Supervisor: Dr. Mary Ann Moore

May 2004–May 2005  
*University of Rhode Island and University of Massachusetts Dartmouth*

**MBA coursework**

Sept.1999-May 2001  
*Philadelphia University, Philadelphia, PA USA*

**M.S. Textile Engineering**

Thesis: Beyond Roller Drafting in Short Staple Spinning  
Supervisor: Professor Herbert J. Barndt

Jun 1984 – Aug. 1988  
*P.S.G College of Technology- Barathiar University, Coimbatore- India*

**B. Tech. Textile Technology**

Project: *Computer Applications and Quality Control in Yarn Manufacturing*

COURSE WORK

**Clothing & Merchandising**


**Statistics/Proc. Quality Control**


**Textile Science/Manufacturing**


**MBA**


**Computing**

Minitab, SPSS, SAS, Stata, Design Expert, MathCAD, Microsoft office

AWARDS

*Florida State University, Tallahassee, FL, USA*

Sept. 2010  
Hugh Stephens and Ameeta Parikh Endowed Scholarship Award, Department of Retail Merchandising and Product Development,
College of Human Science (US$ 300)

Dec. 2008  Dissertation award recipient, Department of Textiles & Consumer Science, College of Human Science (US$ 500)

Sept. 2008  Hugh Stephens and Ameeta Parikh Endowed Scholarship Award, Department of Textiles & Consumer Science, College of Human Science (US$ 500). (US$ 250)

Sept. 2008  Vereen Family Scholarship, Department of Textiles & Consumer Science, College of Human Science (US$ 500). (US$ 1000)

May 2007  Hugh Stephens and Ameeta Parikh Endowed Scholarship Award, Department of Textiles & Consumer Science, College of Human Science (US$ 500). (US$ 400)

P.S.G College of Technology- Barathiar University, Coimbatore, India

May 1988  Best Outgoing Textile Undergraduate Student

RESEARCH

Summer 2008  Durability of functional Nano-finishes in apparels

Fall 2008/2010  Optical Spun Yarn Diameter: On-line Control and Analysis of Count

Supervisor: Dr. Mary Ann Moore

Summer 2007  Study of Nano-finishing Reusable Surgical Gown Fabric

Supervisors: Dr. R. Cloud and Dr. J. Schlenoff (Florida State University).

2005 - 2006  Acrylic chenille yarn production and quality improvement project for

Quaker Fabrics Corporation of Fall River, Massachusetts

TEACHING EXPERIENCE

Retail Merchandising and Product Development (RMPD), College of Human Sciences, Florida State University, Tallahassee, FL, USA

Spring 2009  Instructional Development of Online course modules

Fall 2006/7  Physical and chemical evaluation of textile materials

Spring/Fall 2008  Laboratory identification and analysis of textiles

Department of Textile Engineering, Moi University, Eldoret Kenya

1996-1998  Textile Chemistry II; Advanced Weaving Studies; Textile Testing I

Quality Control of Textile Processes; & Knitting Mechanisms
## INDUSTRIAL EXPERIENCE

<table>
<thead>
<tr>
<th>Date</th>
<th>Organization</th>
<th>Position</th>
<th>Responsibilities</th>
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| Jan. 2010 - Present| Meridian Specialty Yarns Group Inc.               | Projects Manager                              | Product Development  
Quality improvement and evaluation  
*Glen Raven Custom Fabrics, LLC, Anderson, SC.*                                                               |
| May 2008 – August 2008 | Glen Raven Custom Fabrics, LLC, Anderson, SC.     | Quality improvement and evaluation of novelty yarns and fabrics  
Capacity and quality assessment of novelty yarn suppliers and manufacturers                                  |
| July 2001 – July 2006 | Quaker Fabrics Corporation, Fall River, MA USA   | Senior Textile Engineer                       | Establish product structures and bill of materials  
Responsible for color matching yarn mixes for new and replacement  
Prepare and transmit standards to production departments  
Translate and maintain vendor and customer product specifications  
Provide technical assistance to spinning departments  
Issue guidelines and recommendations on specific processes |
| January 1994-April 1996 | Rift Valley Textiles Ltd., Eldoret, Kenya  | Assistant Standards and Quality Control Manager | Quality control operations  
Preparation of quality and company periodical reports                                                        |
Study and optimize machine parameters, product and quality  
Analyze productivity and formulate suitable metrics for productivity  
Company representative on national textiles standards committees |