**THE HONG KONG POLYTECHNIC UNIVERSITY**

**INSTITUTE OF TEXTILES AND CLOTHING**

# TWIST LIVELINESS OF SPUN YARNS AND THE EFFECTS ON KNITTED FABRIC SPIRALITY

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A thesis submitted in partial fulfilment of the requirements for

the Degree of Doctor of Philosophy

July 2007

# CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgment has been made in the text.

MURRELLS, CHARLOTTE

***This Thesis is Dedicated to My Parents***

# ABSTRACT

This thesis is concerned with a systematic study of the measurement of yarn twist liveliness and of its quantitative relationship with single jersey fabric spirality.

Firstly, investigations were carried out on a methodology and apparatus to be used for evaluating the twist liveliness of spun yarns by the wet snarling method. Optimisation of both the methodology and apparatus was undertaken so that the procedure could be applied with confidence in a standard and practical manner. Examined through intra and inter laboratory studies, it has been shown to produce accurate and repeatable measurements of twist liveliness over a range of 100% cotton ring spun yarn counts from 29.5tex to 84.4tex.

As part of any investigations to develop systems that can minimise the residual torque induced in ring spun yarns, it is essential to quantify and accurately evaluate the yarn twist liveliness in a standard manner. The established methodology and apparatus were used to measure twist liveliness of 100% cotton modified Nu-Torque™ singles ring yarn, in comparison with conventional ring yarns. The effects of twist, fibre type and downstream processing on the twist liveliness of the yarns were examined. An analysis of the reduced twist liveliness was carried out in a production trial during which the spinning system was in control and was therefore stable.

The effect of twist liveliness on the spirality of single jersey fabrics has long been recognised and spirality has been investigated previously by use of empirical methods. The present study has used, for the first time, an artificial neural network to determine the relationship between the measured twist liveliness of spun yarns and the degree of spirality of pure cotton single jersey fabrics knitted from the yarns. Multiple regression and artificial neural network models for the prediction of the degree of fabric spirality from measured twist liveliness and other contributing parameters were established. It was found that both models have a high ability to predict the amount of fabric spirality although the neural network model produced slightly superior results.

The methodology in the study measures twist liveliness by counting the number of snarl turns formed in yarn samples under test. In order to increase the efficiency of the apparatus in use, investigations were conducted with a view to replacing the manual counting of the turns by an automated method using image processing techniques. An image acquisition unit was constructed to obtain images of the yarn samples. Fast Fourier Transform (FFT) and Adaptive Orientated Orthogonal Projective Decomposition (AOP) were used to extract the snarling characteristics and record the number of snarl turns from the captured images. Statistical analyses confirmed that the measurements obtained by the automated method agreed well with the original method of using a twist tester to count the number of snarls for low snarling yarns of medium counts.

# LIST OF PUBLICATIONS

**Refereed Journals**

Murrells, C.M., Tao, X.M., Xu, B.G., and Cheng, K.P.S., An Artificial Neural Network Model for the Prediction of Fabric Spirality of Fully Relaxed Single Jersey Fabrics, submitted to the Textile Research Journal, accepted for publication.

Murrells, C.M., Xu, B.G., Tao, X.M., and Cheng, K.P.S., A Methodology to Assess Spun Yarn Twist Liveliness: Principles, Apparatus and Evaluation, to be submitted to the Textile Research Journal.

Xu, B.G., Murrells, C.M., and Tao, X.M., Automatic Measurement and Recognition of Yarn Snarls by Digital Image and Signal Processing Methods, submitted to the Textile Research Journal, accepted for publication.

Xu, B.G., Murrells, C.M., Tao, X.M., Computerized Characterization of the Yarn Snarling Distribution, Journal of Textile Research, Vol. 27, No.10, p.9-13 (2006).

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Murrells, C.M., Wong, K.K., Hua, T., Leung, C.L., Xu, B.G., Yang, K., Wong, S.K., Cheng K.P.S., and Tao, X.M., Study of Yarn Snarling in Nu-Torque™ Singles Ring Yarns, p.401-404, Proceedings of The Textile Institute 83rd World Conference, May 23-27, Shanghai, China, (2004).

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# ACKNOWLEDGEMENTS

I would like to express my utmost gratitude to my chief supervisor, Professor Xiao-ming Tao, for providing the opportunity for this project to be undertaken, and for her comprehensive assistance and valuable advice.

I would like to express my appreciation to my co-supervisors Dr Kwok-po Cheng and Dr Bin-gang Xu for their technical advice, suggestions and comments. Special thanks to Dr Ka-kee Wong for her endless support, advice and helpful discussions during the course of my study.

My grateful thanks are also given to Mr Sing-kee Wong, Dr Tao Hua, Dr Kun Yang, Mr Paul Leung, Ms Linda Chan, Ms Helena Liu, Mr Alan Ho, and Mr Raymond Li for their support and kind assistance in the experimental works.

My sincere appreciation is given to the laboratory technicians in the workshops of the Institute of Textiles and Clothing especially Ms. Mow-nin Sun and Mr Kwan-on Choi in the Control and Physical Testing Laboratories and Mr Wai-man Chu and Mr Kin-ho Fan in the Spinning Workshop for their technical support and help.

Many thanks are also extended to all the people and testing laboratories that participated in the intra and inter laboratory studies.

I would like to thank my family and friends for their constant encouragement, understanding and moral support throughout my study.

Finally I would like to acknowledge The Hong Kong Polytechnic University for the facilities and financial support granted to me to carry out this research project.

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# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND

Since ancient times, yarn has been made by spinning or twisting together short lengths of various types of fibres in order to produce a long continuous length suitable for weaving or knitting into a fabric. This twist insertion to bend the fibres into approximately helical shapes is an essential process in yarn spinning because it helps to bind the constituent fibres together by frictional forces so as to provide strength and give the yarn coherence (Hearle, Grosberg & Backer 1969, p.63). However, the fibres are then prone to generate a torque when they try to release the strain energy arising from the stresses built up as a result of the twisting action. Consequently this yarn torque causes newly spun yarn to display a tendency to untwist or snarl prior to any relaxation methods that might be subsequently applied to the yarn. This property of a yarn is called twist liveliness (Primentas 1995).

Generally, in the textile industry twist liveliness is considered a negative attribute of a spun yarn. Many workers have identified that the twist liveliness or residual torque of spun yarns is one of the major contributing factors leading to spirality problems of fabrics. Spirality is a distortion of the fabric which is a complex phenomenon arising from several factors (Lau, Tao & Dhingra 1995). However, although it is known that twist liveliness of a yarn is one of the most prominent of these factors, the quantitative relationship between twist liveliness and fabric spirality has not been determined. In the conventional yarn manufacturing process, the yarn twist liveliness property is not evaluated which may be because the twist liveliness of a conventionally spun yarn is very high. Such yarns are only used after being further processed in order to considerably reduce the effects of the yarn torque. Therefore, in industry, it is probably thought adequate to give an indication of the amount of twist liveliness of conventionally spun yarns by reference to the level of yarn twist e.g. if the level of yarn twist is higher, it may be considered that the twist liveliness of the yarn is greater.

Normally a newly spun yarn is processed so as to substantially reduce the yarn's twist liveliness characteristics. Traditionally, these processes include setting the yarn by using steaming or chemical treatments and balancing the yarn torque using means such as plying two identical single yarns with a twist in the opposite direction. Both methods result in several disadvantages mainly involving increased costs, fibre damage or only temporary suspension of the yarns' untwisting tendency.

As a consequence of these disadvantages, investigations have been undertaken over the years to find a method that can directly balance the torque in the yarn during the spinning process. Thus a low twist lively yarn is produced without having to be subject to the disadvantageous further processing methods.

Most recently, Tao and Xu (2005) and Tao, Xu and Wong (2006) have successfully developed a system to directly balance the yarn torque in singles ring spun yarns during the spinning process by using a false twisting concept. This method has been registered under the trademark 'Nu-Torque$^{TM}$ singles ring yarns'. An advantage of this modified spinning method is that a low torque yarn can be produced in a single step thus saving processing time and reducing processing cost. As it is the main aim of the Nu-Torque spinning system to balance yarn torque and hence reduce twist liveliness, it then becomes important to measure the actual yarn twist liveliness itself in the evaluation of the system rather than using yarn twist as an indicator.

Previously, various measurement devices and procedures relevant to the measurement of yarn torque and twist liveliness have been examined. They have approached the problem from different points of view and can be divided into three categories namely direct, semi-direct, and indirect measurements (Belov et al 2002a). However, although these several methods have been proposed, it would appear that a standard methodology has not been adopted because there are conflicting opinions (Milosavljevic & Tadic 1995; Tao, Lo & Lau 1997) as to which technique is appropriate. There is therefore a need to develop a new methodology suitable for use as a standard in measuring the important aspect of twist liveliness in spun yarns.

With the development of an effective methodology to measure twist liveliness it would have the potential to be of assistance in the evaluation of the spirality of fabrics knitted from twist lively yarns. As pointed out by Lau, Tao and Dhingra (1995, p.95), spirality '…affects both the aesthetics and functional performance of the knitted material and the garments produced from it' and it would be helpful to manufacturers if a predictive model could forecast the degree of fabric spirality accurately. Although a number of models using several yarn and fabric characteristics have been proposed in the past, they have not included twist liveliness as a criterion and they have mainly been of limited complexity. As it is generally agreed that twist liveliness is a major contributor to spirality problems, it is considered that using values of twist liveliness as one of the parameters in a comprehensive mathematical model would result in a better representation of actual conditions in predicting spirality. This is particularly relevant as modern low torque yarns are now available. There is therefore a need to establish a suitable model.

In summary, there has been only very limited advancement in the establishment of an effective methodology to assess twist liveliness and the quantitative relationship between twist liveliness and fabric spirality has not been examined. The development of a standard technique to measure twist liveliness is thus desirable as it could facilitate the exploration of methods to reduce the twist liveliness of yarns, for example by introducing modified, cost effective spinning systems, and it could lead to the accurate prediction of fabric spirality.

## 1.2 OBJECTIVES

The aim of the project is to establish a methodology for the measurement of twist liveliness with a particular emphasis on its application to assess the recently developed Nu-Torque singles ring yarns and conventional ring spun yarns, and with a view to establishing the ability to predict the spirality of single jersey knitted fabrics. Specifically, the principle objectives of this project can be described as follows:

(1) To develop a methodology for the measurement of yarn twist liveliness for laboratory and industrial applications.

(2) To develop a test apparatus and automated system for the measurement of yarn twist liveliness.

(3) To apply the methodology to evaluate the twist liveliness properties of Nu-Torque yarns and to assess the process capability of the Nu-Torque system.

(4) To establish a mathematical model for predicting the spirality of single jersey knitted fabrics from measured twist liveliness and other contributing factors within the normal range of fabric parameters.

## 1.3 METHODOLOGY

To achieve the objectives of the project, the following research methodology will be employed:

(1) A literature review will be conducted with the aim of gaining relevant background knowledge and to find out about recent developments within the study areas.

(2) From a review of existing measurement systems a suitable technique will be selected that can measure the twist liveliness of spun yarns based on recommended testing criteria. An apparatus will then be designed and built taking into consideration different factors that may influence the validity and reliability of the measured results obtained. Furthermore, a testing protocol will be established to ensure that the results are accurate and reproducible.

(3) The precision of the apparatus and methodology will be evaluated according to the ASTM Standard E 691-05 by repeated testing of identical yarn specimens within the same laboratory (intra-laboratory) and between different laboratories (inter-laboratory).

(4) The developed apparatus and methodology will be employed to investigate the twist liveliness of a 100% cotton, 29.5tex, Nu-Torque singles ring yarn compared to a conventional ring yarn with a similar specification. The effects of different

variables on the twist liveliness of the yarns will be examined. In addition, during a small scale production trial, the twist liveliness of 100% cotton, 29.5tex, Nu-Torque yarn with optimum parameters will be measured. The performance and capability of the modified ring spinning system will be evaluated using statistical tools.

(5) In order to establish a model for predicting the spirality of knitted fabrics from measured twist liveliness and other contributing factors, the first step will be to use a modified IWS test method TM276 to measure the spirality of fabric samples. The study will cover 100% cotton single jersey fabrics produced on circular knitting machines from 29.5tex conventional singles ring yarns, Nu-Torque singles ring yarns and plied yarns. The twist liveliness of the yarns will be evaluated using the developed methodology and apparatus. Correlation between the measured spirality, the measured twist liveliness and other factors contributing to spirality will be examined. Two methods of modelling the relationship between the various factors in order to predict the fabric spirality will be investigated. Firstly, a linear multiple regression method will used and secondly, an artificial neural network concept will be applied and a comparison between the performance of the two models will be made on samples that had not been used in model development or training.

(6) To improve the developed method to measure twist liveliness that had been used in the investigation of the modified ring yarns and the prediction of spirality, an image analysis system will used to automate one part of the procedure. This is to ensure that the overall measurement process will have a low turnaround time as such requirements are necessary if the method is to be used in industry. The image based system will be established by first developing a suitable image acquisition unit and then processing the images captured by using image analysis. The developed system will be tested with 100% cotton, Nu-Torque ring yarns over a range of yarn counts.

## 1.4 SCOPE OF THESIS

This thesis consists of seven chapters. The first chapter is intended to introduce the background which describes the need to conduct this study, the aims and objectives and the methodology and scope of the thesis.

Chapter 2 provides a review of past and current research work associated with the present study. It covers various topics such as twist liveliness in yarn manufacture and processing; the causes of twist liveliness and the practical implications of twist lively yarn; methods for reducing twist liveliness and previous methods employed for measuring twist liveliness and for predicting the degree of fabric spirality.

Chapter 3 presents the development of a methodology and test apparatus to measure the twist liveliness of spun yarns based on the indirect method of measuring snarling twist. The apparatus requirements, detailed design aspects and testing procedure are carefully considered so that the measurements made using the developed apparatus and methodology would be accurate and reproducible. Suitable testing variables are selected for 100% cotton ring yarns through experiments. The accuracy or precision of the developed apparatus and methodology is evaluated by repeated testing of several yarn specimens both within the same laboratory and between different laboratories.

Chapter 4 discusses the effects of twist, fibre type and post-spinning processing on the twist liveliness of conventional ring yarns and Nu-Torque singles ring yarns. The performance and capability of the Nu-Torque system to produce yarns with consistently low twist liveliness is assessed.

Chapter 5 investigates the feasibility of multiple linear regression and artificial neural network methods to predict fabric spirality from twist liveliness measured using the developed apparatus and methodology and other factors contributing to the degree of spirality. Investigation of the correlation between the parameters and the degree of spirality are carried out. A comparison is made between the neural network and the multiple linear regression models.

Chapter 6 describes the investigations conducted to improve the efficiency and operational aspects of the apparatus developed for the measurement of twist liveliness. This work proposes an image based system to automatically count the number of snarl turns along the yarn sample length under test. A comparison is carried out between measurements made using the automated method and the original method of counting the number of snarls using a twist tester. Finally, Chapter 7 provides a summary of the whole study and general conclusions as well as recommendations for future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

Twist liveliness of a yarn is due to the release of the residual torque that arises from the insertion of twist in the yarn during spinning. It is of practical significance in problems related to the downstream processing of yarn. This chapter covers a literature review of previous studies and analyses of the torque generated during spinning of staple fibre yarns, the implications of twist lively yarns in textile manufacture and methods to reduce and assess twist liveliness.

## 2.2 TWIST LIVELINESS IN YARN MANUFACTURE AND PROCESSING

### 2.2.1 Causes of Twist Liveliness

An unset, newly spun twisted yarn is twist lively due to the presence of yarn torque that builds up in the fibres during twist insertion in the spinning process. In mechanics, torque is a measure of how much of a force is acting on an object causing that object to rotate and the SI unit of torque is the Newton-metre. After spinning, as textile fibres are viscoelastic materials, subsequent partial relaxation of the yarn torque will occur with time. If a twist lively yarn is free from constraint, it will untwist to release the torsional stresses inside it, in order to acquire the natural configuration of a minimum energy state (Tao, Lo & Lau 1997).

In a staple yarn, the residual torque is dependent on the mechanical state of the constituent fibres and the yarn geometry. These factors in turn depend on the type of fibres used and yarn structure (Postle, Burton & Chaikin 1964; Bennet & Postle 1979a). As different types of textile fibres possess different moduli (tensile, bending and shear) and different cross sectional shapes, this will lead to different levels of torsional stress induced in the yarn (Lau, Tao & Dhingra 1995). Yarn structure, such as the arrangement of the fibres and fibre migration, affects the twist of the yarn and the distribution of fibre stress and thus also influences the level of torque generated.

Over the years, several researchers have analysed the initial values of torque generated in newly twisted singles yarns as created by three components namely fibre bending, fibre torsion and fibre tension and by considering different forms of yarn geometry. The earliest analysis using a force method was carried out by Platt, Klein and Hamburger (1958). They derived expressions for yarn torque due to the fibre bending $M_B$ and torsion component $M_T$ shown in Equations (2.1) and (2.2) assuming helical yarn geometry and linear fibre elasticity.

$$M_B = \frac{N_f E_f I_f}{R_y}\left[\frac{\log_e \sec\theta_8 - \sin^2\theta_8}{\tan\theta_8}\right] \tag{2.1}$$

and

$$M_T = \frac{N_f K_f G_f}{R_y}\left(\sin\theta_8 \cos\theta_8\right) \tag{2.2}$$

where $N_f$ = total number of fibres in the yarn cross section

$E_f$ = fibre modulus of elasticity in bending

$I_f$ = moment of inertia of the fibre cross section

$K_f$ = torsional moment of inertia

$G_f$ = modulus of elasticity in torsion of a fibre

$R_y$ = yarn radius

$\theta_8$ = yarn surface helix angle.

Postle, Burton and Chaikin (1964) also used a force method and assumed an idealised helical yarn geometry and linear fibre elasticity in tension, torsion and bending to estimate the torque in a twisted yarn. They demonstrated that fibre tension is the most important component contributing to the total torque in a twisted yarn and that the contributions of fibre bending and fibre torsion are small. They obtained a linear relationship between yarn torque due to fibre tension and twist factor immediately after twisting and relaxation. However, the calculated values of torque due to fibre tension were found to be greater than the measured torque. Postle, Burton and Chaikin

(1964) suggested that this difference was due to the rapid decrease of the fibre stress and yarn torque during and immediately after twisting. Whereas Tandon, Carnaby, Kim and Choi (1995a) point out that the yarn torque is mainly due to the tensile strains in the outer fibres in the model proposed by Postle, Burton and Chaikin (1964). It was observed that when a yarn is twisted at a fixed length the tensile strains will be developed successively from the yarn core to the surface, whereas the outer fibres initially are unstrained. This may account for the theoretical high yarn torque because the contribution of yarn torque due to fibre tension depends on the helix angle of the outer fibres.

Tandon et al (1995a) and Tandon, Kim and Choi (1995b) developed a theoretical analysis to examine the torsional behaviour of singles yarns, which may be bulky and may have non-uniform fibre packing density distribution. It was based on a discrete fibre modelling approach, an energy method, and a shortest path hypothesis. Two different loading cases were considered, the first was the consideration of the yarn torque-twist behaviour at constant yarn length and the second was the torque-twist behaviour at constant yarn tension. The experimental data was found to correspond reasonably well to the theoretical torque-twist relationships. Moreover, the analysis confirmed the findings of Postle, Burton and Chaikin (1964) in that the fibre tension contributed to yarn torque more than the sum of the contributions of fibre bending and fibre torsion.

Bennet and Postle (1979a) derived theoretical expressions for the yarn-torque component due to fibre tensile stresses for two limiting forms of yarn geometry, namely with no fibre migration and with perfect fibre migration. It was found that, in practice, the level of torque generated in a yarn is highly dependant on the fibre tensile-stress distribution. This distribution is determined by factors, such as yarn geometry and the mode of twisting, which influence the extent to which fibres are free to migrate through the yarn cross section. For statically twisted staple fibre yarns there was a reasonably good correlation between the experimental value and the calculated torque values for a perfectly migrating yarn as shown in Equation (2.3), except at high twist levels and for relatively coarse wool and polyester yarns. In addition, the yarn torque generated under low tension levels was found to be due equally to the three components of torque namely the torsional, bending and tensile stresses in the fibres of these statically twisted yarns. However, as the latter component is directly related to the applied tensile stress in the yarn, under practical conditions higher levels of torque would be found in yarns produced by a continuous spinning process. This is because the yarn is subjected to much larger tensile stresses during the process as compared with static twisting applied as part of laboratory investigations.

$$M_E = PR_y \left\{ \frac{\sec^3\theta_8 - 3\sec\theta_8 + 2}{3\tan\theta_8(\sec\theta_8 - 1)} \right\} \tag{2.3}$$

where $M_E$ = torque component generated by fibre tensile stress

$P$ = applied tensile force

$R_y$ = yarn radius and $\theta_8$ = yarn surface helix angle.

### 2.2.2 Effects of Twist Liveliness

Generally, in the textile industry twist liveliness is considered to be a negative attribute of a spun yarn as it significantly contributes to the problems of snarling and spirality in yarn processing and fabric production.

#### 2.2.2.1 Yarn snarling

Snarling occurs when a twist lively yarn is given sufficient slack and, with this reduced tension, the yarn will retire into itself and simultaneously twist in the opposite twist direction. This is also known as the torsional buckling effect as shown in Figure 2.1 (Primentas 2003e). Snarling due to yarn twist liveliness has been identified as a cause of yarn breakage, a reduction in a yarn's properties and equipment malfunction (Primentas 2003e).

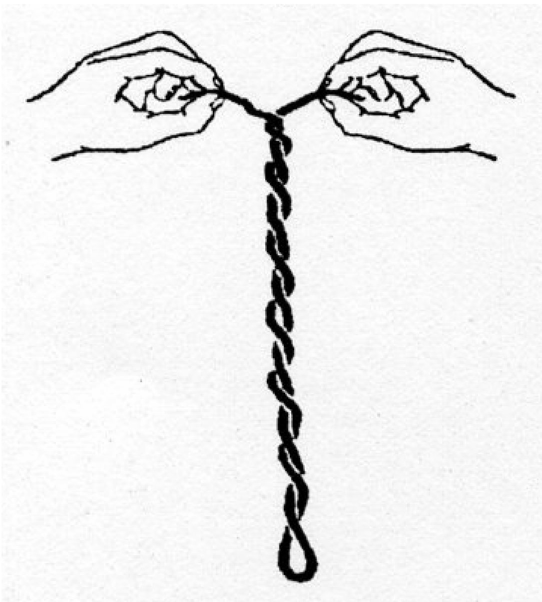
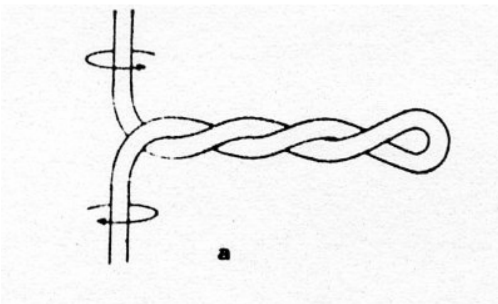


**Figure 2.1 Snarling in a twist lively yarn**
(Source: Heberlein 2002)

It is interesting to note that, as reported by Belov, Lomov, Truevtsev, Bradshaw and Harwood (1999b, p.61; 2002a, p.342), snarling is not just restricted to textile applications but can also be observed in the field of pure and applied science such as the twisting and coiling of DNA and proteins and the looping and kinking of underwater cables 'where there is a loading of a long slender structure by the axial moment and the force'.

Hearle and Yegin (1972b) identified that when a snarl is formed as a yarn is allowed to contract it will either have the appearance of one of two types as shown in Figure 2.2 (a) and (b). The first is the usual snarl appearance or the 'bicomponent helical snarl' which has a similar appearance to a two-fold yarn with its axis perpendicular to the unsnarled yarn axis. The second 'single component helical snarl' resembles a tightly coiled helical spring and has its axis parallel to the unsnarled yarn axis. In practice, the second single component helical snarl does not occur unless the yarn has been subjected to very high twist.



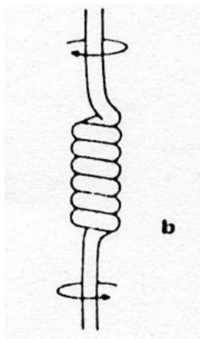




**Figure 2.2(a) Bi-component helical snarl** **Figure 2.2(b) Single component helical snarl**
(Source: Hearle & Yegin 1972b)

The snarling mechanism is controlled by yarn parameters such as internal torque, yarn tension, yarn bending rigidity and torsional rigidity. The modelling of snarl formation in textile yarns can be based on the model of an elastic string. (Belov, Lomov, Truevtsev, Bradshaw & Harwood 1999a, 1999b, 2002b).

Hearle (1966) and Hearle and Yegin (1972a) analysed the snarling mechanism in torque-stretch yarns produced by the twist-set-untwist method on a false twist machine. It was stated that the snarling mechanism is an example of the elastic instability in a cylinder subjected to torque. Figure 2.3 illustrates the transformation of a straight rod under a tension $P_{f,0}$ to a full snarl under zero tension. The creation of one turn of snarl removes one turn of twist from each end of the rod, however because the snarl has a helix angle θ this leads to the removal of a total of 2cosθ turns. The twisting energy is reduced, but acts against an increase of the potential energy of the applied tension and the development of bending energy in the snarl.

The relationship between the tension and reduction in length (twice the length of the rod in a snarl) is given by minimising the total energy U, and considering the twist energy $U_T$ and bending energy $U_B$ where;

U = potential energy + twist energy + bending energy (2.4)

$$= P_f\left(L_o - L\right) + U_T + U_B$$

The symbols are shown in Figure 2.3.

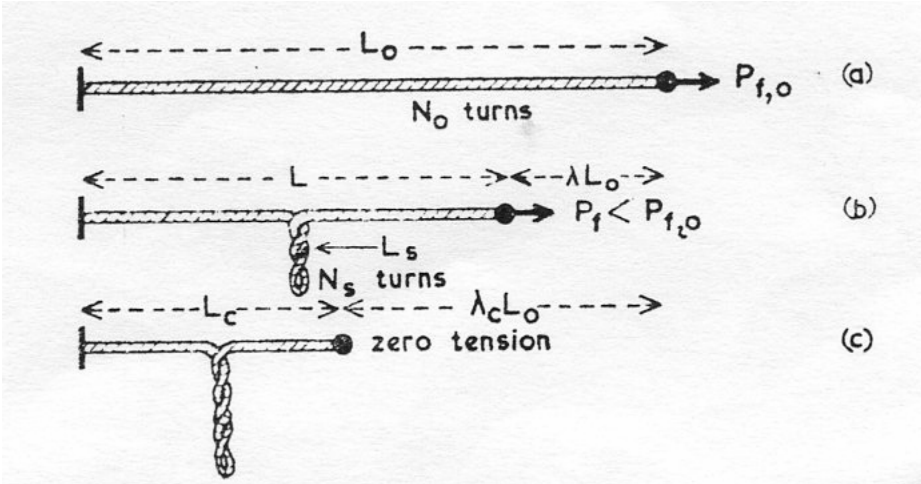



**Figure 2.3 Snarling in a twisted rod at reducing tension. λ is extension ratio**
(Source: Hearle 1966)

For the prevention of yarn snarling in processing, the critical parameters of snarling and loop formation were studied by Belov et al (2002a, 2002b). The critical parameters were identified as the critical torque, tension, twist and slack corresponding to loop and snarling formation. It was determined that the critical parameters could be predicted from three models by Timoshenko (1961), Ross (1977) and Dwivedi, Das Talukar and Mahmood (1990) if the non-linear torsional behaviour of yarn is accounted for.

The first classical work was by Timoshenko (1961) and was based on the theory of elastic stability. The following relationship was proposed for the stability of a homogeneous elastic thread of circular cross section subject to axial torque and tension.

$$M_c^{\ 2} = 4EIF_c + 4(EI)^2\pi^2 / L^2 \tag{2.5}$$

where $M_c$ = 'critical torque'(residual torque)

$F_c$ = 'critical tension'

L = length of the string

EI = the bending rigidity

'critical' refers to the point at which the yarn suddenly deforms into a snarl.

The work by Ross (1977) was based on an investigation of the mechanics of kinking of electromechanical cables in underwater applications. The second criterion for critical torque and tension was derived by Ross (1977) based on the formation of a plain circular loop in a long elastic string subjected to terminal torque and tension and is given by:

$$M_c^{\ 2} = 2EIF_c \tag{2.6}$$

A similar approach was used by Dwivedi, Das Talukar and Mahmood (1990) to produce Equation (2.7) based on an assumption concerning the loop geometry and provides an estimation of critical parameters that lie between those predicted by Timoshenko criteria (Equation 2.5) and the Ross criteria (Equation 2.6).

$$M_c^{\ 2} = 2.28EIF_c\,. \tag{2.7}$$

An analysis of the relationships in Equations (2.5) to (2.7) shows that an increase in tension decreases snarling. In addition, the residual torque depends on tension F and the initial bending rigidity EI. Examination of the Equations (2.5) to (2.7) led Belov et al (2002a) to propose the use of a non-dimensional parameter *m* to assess the tendency of a yarn to snarl:

$$m = \sqrt{\frac{M^2}{EIF}} \qquad (2.8)$$

where M = residual torque

F = tension

EI = bending rigidity

The higher the value *m*, the higher is the yarn twist liveliness and if $m < 2$ snarling is prevented. In a further study Belov et al (2002b) developed a model to understand the mechanism of loop formation and elimination. From this model a relevant insight into the mechanism of snarling is obtained; it also provides a criterion for loop formation and allows for the prediction of the shape and size of the loop formed.

#### 2.2.2.2 Fabric spirality

Plain knitting is important in industry as it consists of approximately 90% of all knitted fabric consumption (Chen 2002) and any problems, such as spirality, relating to these fabrics are therefore of major commercial significance. The plain knit structure is the simplest form of weft knitting and is the base structure of single jersey fabrics. It is made up of a ‘single length of yarn formed into a repeating pattern or matrix of interlocking loops’ (Doyle 1952, p20). Most single jersey fabrics are produced on circular knitting machines. In knitted fabric structures, the horizontal rows of loops are called courses and the vertical columns of loops are called wales. The technical face of the fabric illustrated in Figure 2.4 shows that the side limbs of the needle loops should have the appearance of a vertical column of V’s in the wales that should be parallel to the edges of the fabric and at right angles to the courses. However, in practice, if a twist lively singles spun staple yarn is used in the production of the single jersey fabrics the undesirable phenomenon of ‘spirality’ becomes vividly apparent, in that the wales show a pronounced bias to the left or the right (Primentas 1995, 2003a). This is because the yarn will attempt to rotate inside the fabric, thus lifting one side of a loop out of the surface whilst the other side remains inside the fabric (Lau, Tao & Dhingra 1995).

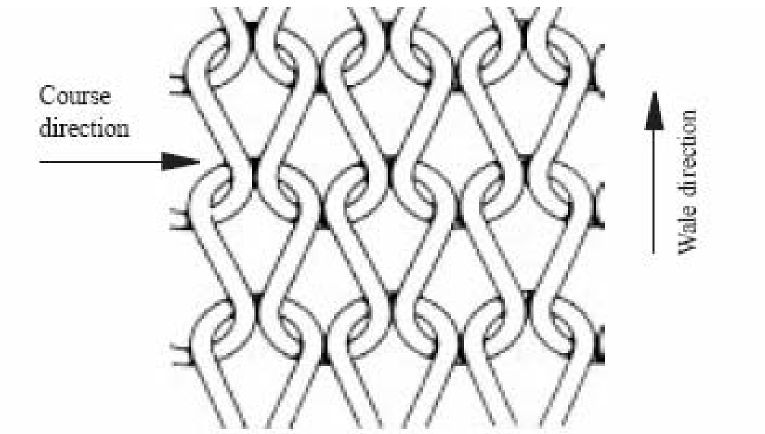



**Figure 2.4 Technical face of a single jersey fabric**
(Source: Ucar 2002)

Early experimental investigations of spirality in knitted wool and cotton fabrics were conducted in 1934 and 1935 respectively by Davis and Edwards. The conclusions that they reached were that the degree of spirality is mainly related to the level of twist in yarn and that cotton and wool yarns behave similarly in causing spirality. The amount of yarn twist has also been ranked by several researchers as a main yarn factor linked to the degree of spirality (Davis & Edwards 1934, 1935; De Araujo & Smith 1989a; Tao J., Dhingra, Chan & Abbas 1997; Chen, Au, Yuen & Yeung 2003). The studies have shown that the angle of spirality will decrease as the twist decreases. In addition, the way a spirality angle will skew is dependent on the direction of twist which can be either in the 'Z' or 'S' direction as shown in Figure 2.5. It was found that Z twist yarns cause the wales to skew to the right giving a Z-skew whereas S-twist yarns cause the wales to skew to the left giving an S-skew to the fabric as illustrated in Figure 2.6 (De Araujo & Smith 1989a).

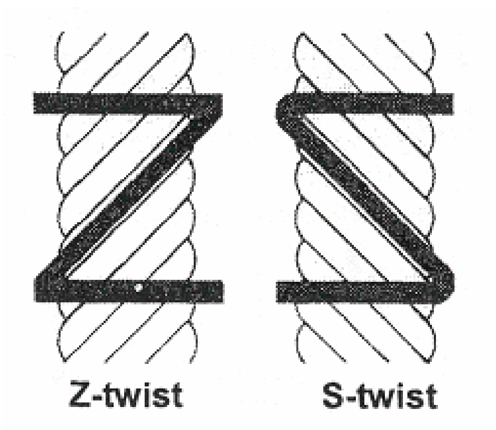



**Figure 2.5 Twist direction**
(Source: Mogahzy & Chewning Jr. 2002)

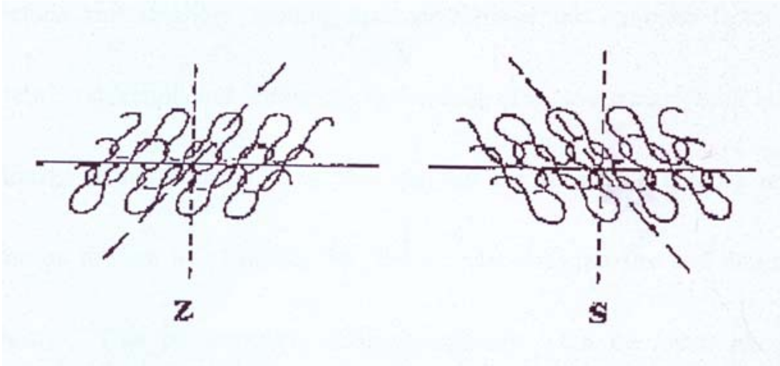



**Figure 2.6 Spirality direction**
(Source: Lau, Tao & Dhingra 1995)

It is, however, generally agreed that the main yarn factor causing fabric spirality is actually the twist liveliness of a yarn caused by the release of the residual torque in the yarn rather than just the presence of twist itself and this was pointed out by Haigh (1987, p.5).

In addition to yarn twist liveliness, many studies have identified various other interacting factors that influence the degree of spirality including the effect of cam box settings (tightness factor), machine gauge, rotational direction, knitting speed and take down tension. A comprehensive review on the effects of these factors on the degree of spirality can be found elsewhere (De Araujo & Smith 1989a; Lau, Tao & Dhingra 1995; Primentas 1995).

## 2.3 METHODS FOR REDUCING TWIST LIVELINESS

Over the years the problem of yarn twist liveliness in spun yarns has been addressed and attempts have been made to reduce it.

### 2.3.1 Traditional Methods

Traditionally, the solutions to minimize the problems caused by twist liveliness involve either setting the yarn by using steaming or chemical treatments or by balancing the yarn torque using means such as plying two identical single yarns with a twist in the opposite direction. Both methods result in several disadvantages mainly involving increased costs, fibre damage or only temporary suspension of the yarns' untwisting tendency.

### 2.3.2 New Developments

As a result of the disadvantages of traditional methods investigations have been undertaken to find a method that can directly balance the torque in twist lively spun yarns.

Tao, Lo and Lau (1997) and Lau and Tao (1997) reported a method to balance the torque in cotton rotor and friction spun yarns respectively. This was achieved by inserting an opposite twist to counterbalance the residual torque in the spun yarn. The yarn strength could be retained after untwisting because of the features of these unconventionally spun yarns such as their core-sheath structures, non-uniform packing density and localised fibre entanglements and wrappings.

The method reported by Tao, Lo and Lau (1997) is not suitable for ring spun yarns because it would result in a significant reduction of yarn strength due to its unique structure. Ring spinning is still the most important yarn manufacturing process in staple fibre spinning because of its capability of producing virtually any yarn count within the spun yarn range and the quality of ring-spun yarns is often unsurpassed. Therefore it would be desirable to produce a singles ring spun yarn with reduced twist liveliness.

Primentas, Iype, Lawrence and Hepworth (1997) and Primentas and Iype (2003c, 2003d) reported a method to deal with yarn torque in cotton ring spun yarns to reduce spirality. This was achieved by steam setting highly twisted yarns and counterbalancing the torsional forces by partially untwisting the steam set yarns to a level of 15 to 30% of their initially introduced twist. The results seem promising but the method still does not overcome the disadvantages of traditional methods.

In another approach, Primentas (1995, 2003b) attempted to reduce the effects of high twist liveliness on fabric spirality by using a modified false twist device used in the texturing of synthetic filament yarns that was mounted on a knitting machine. The concept behind using the false twisting device was that, as the yarn passes through the device, the yarn is untwisted by the number of turns originally put in thus disturbing the yarn torque before the yarn is fed to the knitting zone. The method proved to be unsuccessful as periodic loop distortion occurred in the resultant fabric produced.

Most recently, Tao and Xu (2005) and Tao, Xu and Wong (2006) have successfully developed a system to directly balance the yarn torque in singles ring spun yarns during the spinning process by using the false twisting concept. This method has been registered under the trademark ‘Nu-Torque$^{TM}$ singles ring yarns’. An advantage of this system is that the torque balancing process can be achieved in a single step hence saving processing time and reducing processing cost. In order to evaluate the system an examination of yarn structure, appearance and properties of the Nu-Torque yarns compared to conventional yarns is required. Previous work by Yang (2006) and Hua (2007) explored the yarn structural characteristics and yarn properties. It was found that Nu-Torque yarns have a different structure and have the advantages of low torque, low hairiness and acceptable tenacity compared to conventional yarns. However, an examination of the effect of various factors such as twist, fibre type and downstream processing on the twist liveliness of Nu-Torque and conventional yarns had not been examined. Furthermore, the processing capability of the Nu-Torque system to produce yarns with low twist liveliness had not been explored.

## 2.4 EXISTING METHODS FOR MEASURING TWIST LIVELINESS

Despite the fact that yarn twist liveliness is of practical importance in the textile manufacturing industry and there have been various studies of developments to reduce twist liveliness, a standard measurement of twist liveliness has not been adopted. This may be because there are conflicting opinions (Milosavljevic & Tadic 1995; Tao, Lo & Lau 1997) as to which of the previously proposed techniques might be suitable. However, a standard technique is desirable as it could facilitate in the development of processes to reduce the twist liveliness of yarns and would assist spinners in monitoring the production of yarn and to identify which yarns might cause post-spinning problems.

The previous measurement devices and procedures relevant to the measurement of twist liveliness can be divided into three categories namely direct, semi-direct, and indirect methods (Tavanai, Denton & Tomka 1996; Belov et al 2002a).

### 2.4.1 Direct Method

In the direct techniques, the torque associated with the twist in a yarn is directly measured. In these direct measurements, a torsion balance apparatus has been utilized to measure the torque-twist and torque-recovery characteristics of yarns or fibrous strands. An idealized torsion balance involves attaching one end of a twist lively yarn of specified length to a torsion disc, with the other end fixed. The torsion disc is attached to a torsion wire of known torsional stiffness. An indicating device is positioned between the specimen and the torsion wire. As the specimen is twisted, the torsion wire head is rotated manually so as to maintain the indicating device freely in a constant position or, alternatively, the head may be fixed and the torque measured by the rotation of the indication device (Morton & Permanyer 1947; Dhingra & Postle 1974). However, several variations to the idealized torsion balance have been constructed; for example Peirce (1923) used a magnetic couple instead of a torsion wire.

Dhingra and Postle (1974) constructed a torsion balance apparatus to study the torque-twist and torque-recovery behaviour of both monofilament and multifilament yarns under constant applied tension using an optical lever system. It employed the use of a photopotentiometer to measure the instantaneous rotation of the torsion wire as the specimen is twisted. Initially the original multifilament yarns had a nominal S twist of 0.3 turns/cm which was removed before testing. Bennett and Postle (1979b) similarly used a torsion balance with an optical lever system to experimentally obtain torsional-hysteresis data of continuous-filament and staple-fibre yarns. It was reported that 'untwisted' staple fibre yarns were produced on a worsted spinning frame by drafting the roving to give the correct linear density and inserting the minimum amount of twist necessary to give cohesion to the structure. An Instron tensile tester was used as a basic framework with a twisting mechanism provided by a stepper motor and the angular rotation of the torsion wire was measured using the optical level system in conjunction with a light sensitive photopotentiometer.

An alternative torsional apparatus was described by Noor (1993) to measure the torque-twist curves of fibrous strands. The apparatus consisted of a twisting unit, a torque-measuring unit, a contraction measuring unit and associated data recording devices. The essential features of the apparatus, as described by Noor (1993, p.50), include ‘the use of strain gauges to detect the torque signal and a linear variable differential transformer (LVDT) to measure the linear movement produced by length contraction of the specimen during twisting’.

The difficulties inherent in investigating the low values of torque found in single yarn strands were addressed by Tavanai, Denton and Tomka (1996) by measuring the torsional properties of several ends of yarn or hanks because the higher torque of a hank is easier to measure and a longer length of yarn can be examined in each test. They constructed a Torquemeter similar to that of Morton and Permanyer (1947). It was developed to measure the torsional rigidity of false twist textured yarns by balancing the torque generated by a hank, rather than single yarn strands, against the torque of a torsion wire. The twisting unit was replaced with a means of stopping the rotation of the weight hanging from the hank. They showed that the yarn torque in a single strand could be calculated by dividing the measured hank torque by the number of strands.

Mitchell, Naylor and Phillips (2006) extended the work of Tavanai, Denton and Tomka (1996) by investigating the influence of externally applied tension on the measurement of yarn torque as well as measuring the torsional properties of wet yarns. The torque of the yarn hanks created a rotation of the top end of the hank causing a corresponding torque in the torsion wire. At equilibrium, the torque in the torsion wire was equal and opposite to the torque in the hank. The results were analysed to calculate the amount of torque at zero applied tension and this was taken to be the amount of residual yarn torque. It was pointed out that when measuring yarns with a high twist multiple of 4427 turns $m^{-1}$ $tex^{1/2}$ at low tensions, the hank was no longer being held straight by the applied tension and some buckling and minor localised snarling were occurring which would reduce the net torque. This could indicate a limit to the range of yarns that can be tested to maybe only set yarns or yarns with low twist.

It has been observed that direct measurements of yarn torque are obviously not suitable for industrial use as elaborate and complex apparatus is required (Milosavljevic & Tadic 1995), and, despite the number of academic studies and amount of results obtained from such measurements, the direct method has not been generally adopted for the assessment of twist liveliness.

### 2.4.2 Semi-direct Method

The semi-direct technique measures the tendency of a twist lively yarn to untwist spontaneously when it is free to rotate. Berndt and Beier (1984) reported a semi-direct method or torsion pendulum technique to measure the yarn torque level. The method involves free rotation of a disc that is attached to one end of a vertically suspended twist-lively yarn with the upper end fixed. The disc will rotate and oscillate back and forth until it finally comes to rest. The torque in the yarn can be computed from the oscillation data and other constants, such as disc inertia. The system to evaluate the torque can be measured by one of two approaches; the first one being the difference between the sum of forwards and backward rotations which is the net total number of turns of twist change; the second approach uses a specially designed disc containing holes arranged in a binary pattern which allows infra red senders and receivers to detect the direction of yarn twist liveliness and the number and rate of yarn and disc rotation.

### 2.4.3 Indirect Method

As reported in Section 2.2.2.1 the tendency of a twist lively yarn to untwist due to the unbalanced torsional forces in the yarn will result in snarling and the indirect technique is based on this characteristic. There are two reported methods to indirectly measure the twist liveliness by this torsional buckling property of a yarn when two ends of the yarn are brought together. The first method as described in the Japanese Standard JIS L1095:1990 measures the snarl index by the distance in centimetres between the two ends of the yarn when a snarl begins to form. The second method used by the ISO Standard 3343:1984 specifies a method for determining the twist balance index of folded and cable textile glass yarns. This is achieved by counting the number of snarl turns formed when the two ends of a twist lively yarn are brought into contact. A greater number of turns indicate that the yarn is more twist lively. For convenience, the first measurement will be referred to as the snarling distance and the second measurement as the snarling twist.

Several workers have reported details of indirect methods and apparatus constructed to investigate twist liveliness in their experiments. The earliest technique was reported by Lord, Mohamed and Ajgaonkar (1978) where a length of yarn greater than 20 inches was cut from the specimen and a dead weight was attached to one end and the other end fixed. A small weight was placed at a distance of 10 inches from the ends. The distance between the two yarn ends when the yarn started to snarl when one end was moved towards the other was recorded. This method was also used by De Araujo and Smith (1989a, 1989b) when investigating the nature of spirality.

Primentas (2003e) developed a device called 'Prianic' for similarly testing the snarling distance. The operational principle involves fixing a length of yarn between two jaws of a device. The movable jaw approaches the stationary one as a rotating threaded rod drives it. The yarn forms a U-shape loop and, according to its twist liveliness, a snarl is formed. The snarliness value is given by the measurement of the distance between the two yarn ends at the starting point of the snarl formation.

Theoretical grounds for using the snarling distance to measure twist liveliness were provided by Belov et al (2002a) by using the relationships in Equations (2.9) and (2.10) which include criteria for predicting critical slack in a yarn that would lead to loop formation. The equations provide estimates of the length of yarn forming a loop, $B_l$, developed by Ross (1977) and Dwivedi, Das Talukar and Mahmood (1990)

$$B_l = 2^{\pi EI} / M \tag{2.9}$$

$$B_l = 2.28^{\pi EI} / M \tag{2.10}$$

where M = residual torque

EI = initial bending rigidity

As mentioned, the critical parameters of snarling are torque, tension, twist and slack. The value of slack $B_c$ sufficient for a loop to be formed is directly related to the snarling distance $L_c$.. This is because for a length of yarn, $L$, the critical slack $B_c$ corresponds to the distance that the ends of the yarns are moved toward each other for loop formation thus $L_c = L\text{-}B_c$. This shows that that there is a dependency between $L_c$ and the residual torque, $M$, in Equations (2.9) and (2.10). Therefore, the residual torque in a yarn can be evaluated by the measurement of $L_c$ and using Equations (2.9) or (2.10). However, as reported by Belov et al (2002a) the relationships provide information on loop formation rather than snarl formation due to the introduction of slack. Furthermore, the method is not suited for measuring yarns with low twist liveliness because the distance $L_c$ will be very small and the length of the yarn in the snarl will be of the same magnitude of the whole length of the yarn. Thus the relationships between $L_c$ and $M$ included in Equations (2.9) and (2.10) are only useful for yarns with relatively high levels of residual torque for which the size of the loop formed is much less than the total yarn length.

A simple apparatus capable of measuring both snarling distance and snarling twist was constructed by Milosavljevic, Tadic and Veseilinovic (1994) and Milosavljevic and Tadic (1995). Measurements were taken of the distance between two approaching ends at the moment the open yarn loop begins to snarl, the number of turns in the loop and the total length of the loop at the moment snarling begins. From their results, they proposed that the distance between two approaching ends at snarling formation might be used to give an indication of twist liveliness. An apparatus based on a similar principle of being capable of measuring both the snarling distance and the snarling twist and called a ‘Residual Torque Tester’ was built by Tao, Lo and Lau (1997). The method was based on that of ISO standard 3343:1984 and the apparatus consisted of two clamps and a track where one clamp was attached to one end and the other clamp could be moved along the track. The torsional buckling propensity was measured by clamping the yarn sample at a fixed distance with a pretension of 2cN/tex, a weight was added to the middle of the sample and the apparatus was placed in a water bath. The free clamp was moved towards the fixed clamp and the two snarling parameters (the snarling distance and snarling twist) were recorded. It was found that the measurement of snarling distance produced results with a large variation and, when measuring yarns with low levels of yarn torque, the snarling distance was not sensitive enough to detect the difference in twist liveliness of yarns which had only slight differences in parameters. Consequently, based on these results it was considered that the use of snarling twist would lead to a better measurement of twist liveliness.

## 2.5 PREDICTING THE SPIRALITY OF PLAIN KNIT FABRICS

Although the problem of spirality has attracted extensive research over the years, the accurate modelling or prediction of this phenomenon has not been fully explored as much of the research has gone into understanding the key factors responsible for spirality rather than developing relevant quantitative relationships.

Those few mathematical models that have been proposed to predict the degree of spirality have generally been based on the correlation between spirality and yarn twist and various other interacting factors. For instance, Tao J. et al (1997) determined empirical relationships between the fabric spirality of cotton single jersey fabrics and yarn linear density, twist factor, fabric tightness factor and loop shape factor using statistical techniques. The results showed that the parameters yarn twist and the interaction term involving twist factor and tightness factor account for 94% of the variance in predicting fabric spirality. Similarly, Chen et al (2003) used regression techniques to determine empirical relationships between the spirality of plain knitted wool fabrics and plied yarn and fabric parameters. The regression analyses revealed quantitative relationships between the spirality angle and the twist factor of plied yarn, loop length and fibre diameter in both dry relaxed and simulated industrial relaxed states but that the twist factor of the singles yarn used to produce the plied yarn had no significant effect. Moreover, they found that the tightness factor did not appear to have a significant correlation with the angle of spirality which contradicts previous experimental results.

However, these models do not take into account the predominant factor to affect the degree of spirality, the yarn twist liveliness. The only model to take this factor into account was developed by Hepworth (1993) who investigated theoretically the mechanism by which the use of twist lively yarns leads to spirality in a fabric. Through a computer simulation the shape of a loop in the fabric form could be calculated from consideration of the inter-yarn pressures exerted on a loop by its neighbours. The presence of twist liveliness in the yarn was simulated by introducing a twisting couple acting on the yarn in a loop. Such a model should yield good information about the interactions between twist liveliness and fabric spirality however practical applications may be limited because of the complexities of the model. It is also based on certain assumptions and the success of the model is determined by the feasibility of these assumptions which are not fully explored.

# CHAPTER 3

# A METHODOLOGY AND APPARATUS FOR THE MEASUREMENT OF YARN TWIST LIVELINESS

## 3.1 INTRODUCTION

It has long been recognised that twist liveliness is a property of spun yarn that contributes significantly to problems arising in post-spinning yarn processing and to the phenomenon of fabric spirality. It is therefore important to be able to measure twist liveliness efficiently over a wide range of conditions with a good degree of confidence in the results and to set a standard method of measurement. It is considered that, although previous measurement methods may have been adequate for the purposes for which they were proposed, they generally had somewhat limited application and a new methodology is warranted.

As mentioned in Chapter 1, the scope of this study includes a comparison between conventional yarns and yarns produced by the Nu-Torque modified spinning system. Also covered is the development of mathematical models to predict fabric spirality from twist liveliness and other factors. It is only by first developing a twist liveliness measurement technique that these investigations can be properly undertaken.

As described in Chapter 2, there are three major types of measurement techniques relevant to the assessment of yarn twist liveliness namely direct, semi-direct and indirect.

Direct measurements using a torsion balance apparatus have been widely used to study the torque-twist and recovery characteristics of yarns. This technique was used by Bennet and Postle (1979b) to study their proposed theoretical models by examining the amount of torque applied to an initially twistless yarn when the yarn is statically twisted. In addition, investigations of the relationship of torque and applied tension were conducted. However, the amount of torque generated in commercially spun staple-fibre yarns during the continuous spinning process would be much larger as the yarn is subjected to higher and more variable levels of tension. To test an already twisted commercially spun staple fibre yarn using this technique would only produce results of the measurement of torque generated with the additional twist applied during the test and this would not be an appropriate measure of the yarn residual torque.

Additionally, there are some aspects of this technique using a torsion balance apparatus that would not make it suitable for uses other than for research purposes under laboratory conditions. The instruments have to be extremely sensitive and delicate as the magnitude of torque of a single yarn is very low and the method to prepare and place the yarn sample into the instrument without altering the yarn twist is difficult.

Recently Mitchell, Naylor and Phillips (2006) improved on a direct method by Tavanai, Denton and Tomka (1996) to measure the yarn torque in hanks of worsted wool yarns. This method may have the potential to measure the absolute values of residual torque when comparing yarns of different counts and material. It may also be applicable to theoretical research work and has been used for this purpose when resolving the component of torque due to applied tension and intrinsic torque. However in this case, it was pointed out that when measuring yarns with a high twist factor at low tensions, the samples were no longer being held straight by the applied tension and some buckling and minor localised snarling were occurring which would reduce the net torque. Therefore, this may indicate a limit on the range of yarns that can be tested to perhaps only set yarns or yarns with low twist.

In the past, attempts have been made to evaluate twist liveliness by use of a semi-direct measurement technique of attaching yarn samples to a torsion pendulum mechanism and counting the number of oscillations as the yarn twists and untwists. This method has not been widely used. Although perhaps applicable to some limited laboratory investigative procedures, it is thought doubtful that using this type of oscillating process over a wide range of conditions would lead to a reliable indication of the level of residual yarn torque or amount of twist liveliness of the yarn, which is basically a static characteristic. In other words, for the measurement of twist liveliness it is considered that there are other methodologies which would better meet one of the main testing criteria i.e. there should be a reasonable correlation between the test procedure and the actual problem or end use being evaluated.

A few researchers have used indirect techniques, which are based on the principle that a twist lively yarn will snarl when the two ends of a length of the yarn are brought together. As reported in Chapter 2, there are two types of tests which may be categorised as follows:

- Snarling distance – the distance between the two ends of the yarn is measured when the first snarl begins to form.
- Snarling twist – the total number of snarl turns is counted after the two ends are brought together.

The measurement of the twist liveliness of the yarn is then expressed as the measured length or the number of snarl turns respectively.

Primentas (2003e) has developed an apparatus to measure snarling distance. A drawback to this method is that the relaxation of the yarn in water has not been considered. As textile materials have viscoelastic properties they can store strain energy (i.e. tensile, torsion or bending) from the production process. In air this energy is not recovered completely and it is only accelerated when in the presence of moisture. The relaxation process in water changes the intermolecular structure inside the fibre which releases the torque stored inside the fibre by the breakage and reforming of weak intermolecular bonds such as hydrogen bonds (Lau, Tao & Dhingra 1995; Tao, Lau & Lo 1997). Therefore, measurement in air will not reflect the actual twist liveliness when the yarn is fully relaxed and it is the fully relaxed state which is required to be measured because that equates to the use of the yarn under practical conditions.

Tao, Lo and Lau (1997) and Lau and Tao (1997) measured both the snarling distance and snarling twist of samples of yarn in water in their work. They found that the measurement of snarling distance produced results with a large variation and when measuring yarns with low twist liveliness the snarling distance was not sensitive enough to detect the differences in twist liveliness between the yarns. On the other hand it was found that measuring snarling twist gave reasonably consistent and reliable results and the technique was sensitive enough to detect the difference in the twist liveliness of yarns with low twist liveliness. However, the potential of the methodology and the development of the apparatus were not fully explored.

Therefore, with the disadvantages of previous methods in mind, a new test apparatus and methodology has been developed, and it is the subject of this Chapter, covering an explanation of the design principle and the development of the procedure. Important aspects, such as experimental work conducted to determine the testing variables, i.e. pretension and deadweight, and work to validate the precision or accuracy of the developed measurement system through intra and inter laboratory studies, are included.

## 3.2 THE BASIC MEASUREMENT TECHNIQUE

Several criteria for setting up a good textile test procedure are described by Cohen (1982).

- A textile test should be both valid and reliable, measuring what is being studied and providing consistent, repeatable results;
- The test should be simple to perform and use equipment that is easy to operate and be not too expensive;
- The testing procedure should be capable of being completed within a relatively short time;
- Generally, the test procedure may be accelerated compared to the actual action it is duplicating;
- Correlation should exist between the test procedure and the actual problem or end use being evaluated;

After reviewing the previous work by others and considering the practical aspects of operating a testing system efficiently and effectively, it was judged that a methodology using the indirect method of counting the number of snarl turns would best meet the above criteria. The validity of this decision would be checked by subjecting the new methodology to properly conducted intra-laboratory and inter-laboratory testing.

The principle behind this proposed technique is internationally recognised as it forms the basis of the ISO standard 3343:1984 which specifies a method for determining the twist balance index of folded and cable textile glass yarns. The principle of the test is to count the number of turns a yarn makes on itself when it is arranged in an open loop of specified length and width. The test procedure involves firstly unwinding the first 50 metres of the yarn tangentially from the package so that a representative test specimen is obtained. A further one metre of yarn is then unwound from the package which represents the test specimen and, without cutting the end, the yarn is allowed to hang to form an open loop with the two ends held 100mm apart. Finally, the number of turns, $N_i$, the yarn makes on itself and the direction in which the loop twists (S or Z) are noted which represent the twist balance index. It is mentioned that the counting may be done while untwisting the yarn.

It can be recognised from the description of this testing procedure that the method is very time consuming as the number of turns is counted by the operator. If an operator has to conduct a large number of tests, the reliability and accuracy of the test results would be questionable. Results obtained by different operators may not be reproducible as each step of the procedure is conducted manually.

A test apparatus described in Chapter 2 has been built by Tao, Lo and Lau (1997) using the principles of the ISO standard. This apparatus, called the 'Residual Torque Tester' shown in Figure 3.1, can overcome some of the drawbacks of the entirely manual procedure described above. For example, the ends of the yarn are clamped by a fixed and a movable clamp instead of being held between the thumb and forefinger. A pretension of 2cN/tex is added to the yarn before locking the clamps thus the yarn is initially held under constant tension and, as mentioned in Chapter 2, tension is important as it is one of the critical parameters of snarling. The test is conducted under water which is necessary for the yarn to reach a strain-free state and therefore a dead weight is placed in the middle of the test sample so that the yarn is held below the water surface.

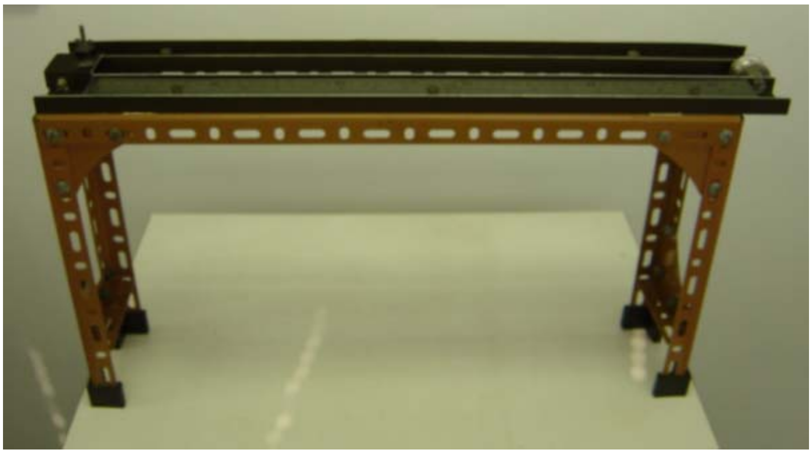


**Figure 3.1 Residual Torque Tester**

However, all the factors which might have the potential to affect the results were not fully considered; for example, the effect of the required pretension and dead weight on the number of snarl turns of yarns with different linear densities. In addition, only one sample can be prepared at a time and the method to accurately count the number of turns was not reported. Therefore, although the basic technique used by Tao, Lo and Lau (1997) and Lau and Tao (1997) showed promise, a new methodology is required in order to produce a system and apparatus that would meet best practices for measuring twist liveliness.

### 3.2.1 Test Procedure Requirements

For measuring twist liveliness in yarns, the following requirements of a methodology are considered essential to produce accurate and reproducible results over a wide range of yarn types:

- Basic principle is to count the number of snarl turns when two ends of a yarn sample of an adequate specimen length are brought together;
- An apparatus and procedure to enable ease of operator use in order to reduce opportunities for errors or inaccuracies to be introduced;
- Specified environmental conditioning of samples to ensure reproducible results;
- Apply pretension to the sample in order to remove snarls or kinks during sample preparation so as to ensure accurate and consistent test length;
- Test specimens to be immersed in water;
- Method to hold specimens below water to be carefully considered;
- Accurate method required for counting the number of snarl turns.

### 3.2.2 Testing Apparatus Requirements

In addition to meeting the above methodology requirements, it is considered that an apparatus for conducting the tests should also comply with the following:

- A straightforward and robust design so that it could be used under industrial conditions if required;
- Sufficiently strong and free from distortion so that inaccuracies would not develop as testing proceeds;
- Corrosion free as water is involved in the test;
- Would allow more than one sample to be tested at a time;
- Capable of extracting samples from yarn specimens wound on cop or cone packages.

### 3.2.3 Apparatus Description

As part of this study three prototypes were designed and produced and their performance assessed. After refining the ideas from the first two prototypes, the final design prototype number three, the ‘Yarn Snarling Apparatus’, was chosen to be used as the final test apparatus and has received a U.S. Patent (Murrells, Wong, Tao & Xu 2007). This test apparatus was designed for evaluating the number of turns when a 50cm length of yarn is twisted on itself. The units used to express the level of twist liveliness of a yarn specimen are the number of turns per 25cm. The apparatus is comprised of a mainframe and a water bath as shown in Figure 3.2.

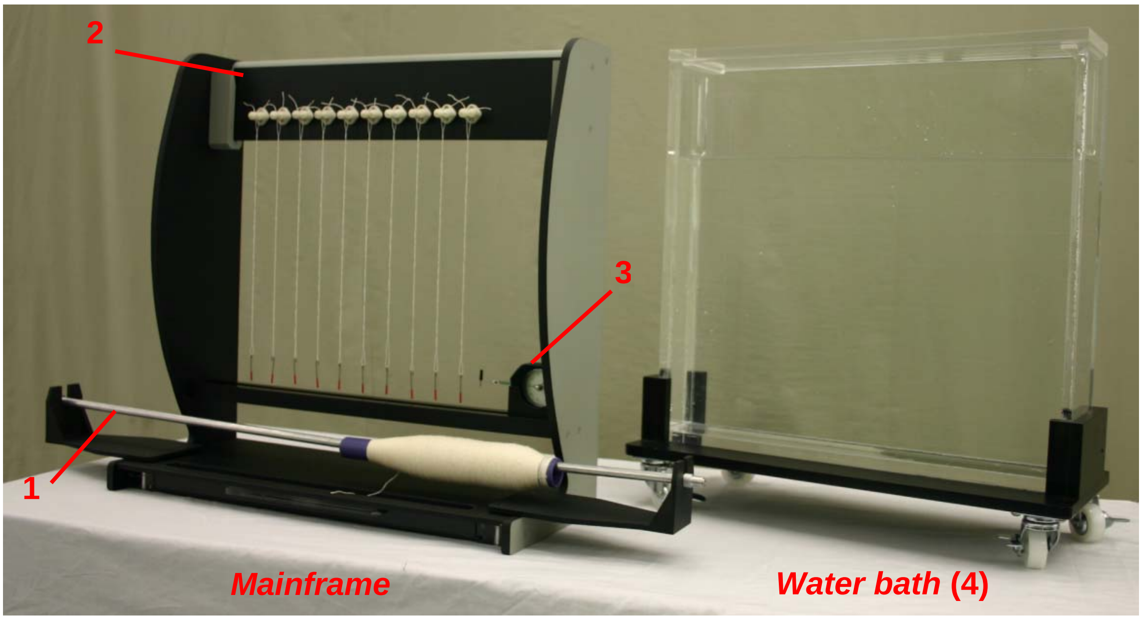



**Figure 3.2 The Yarn Snarling Apparatus**

The components are:

(1) The yarn specimen holder for holding the yarn packages while the yarn samples are drawn off and fixed in the sample holder.

(2) The sample holder which holds up to 10 samples at a time and is slotted into the top of the main frame while samples are fixed in position.

(3) The pretension meter to prevent local deformation of samples.

(4) The water bath for immersion of the samples while held in the sample holder.

Additional items are dead weights for holding the samples below water and a twist tester as a manual method for counting the number of snarls.

The apparatus was designed to allow for the following general operating procedure (a detailed test protocol is described later).

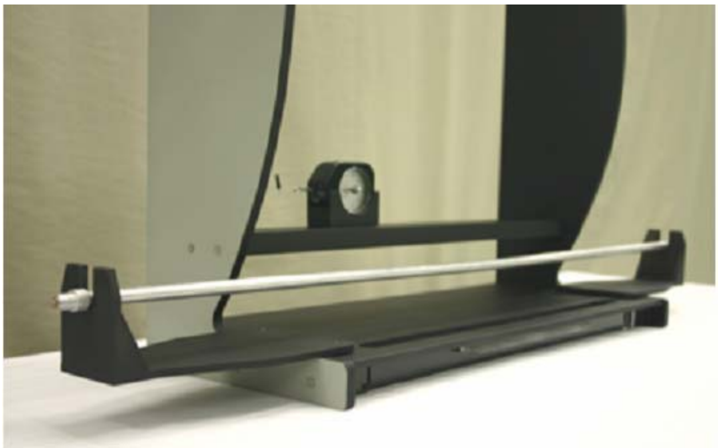
- Yarn samples are to be drawn off from the specimen and the two ends of the yarn are held between clamps on the sample holder. While being drawn off, the sample is pretensioned by use of the pretension meter. A dead weight is placed in the U-shape portion of the yarn sample. Figure 3.2 shows 10 such samples in position on the sample holder.
- The sample holder is removed from the main frame and the samples immersed in the water bath as shown in Figure 3.7 in order for the snarl turns to form in a completely relaxed state.
- The samples are removed from the water bath and the number of snarl turns counted by means of a twist tester as shown in Figures 3.8 and 3.9 respectively.

## 3.3 APPARATUS DESIGN CONSIDERATIONS

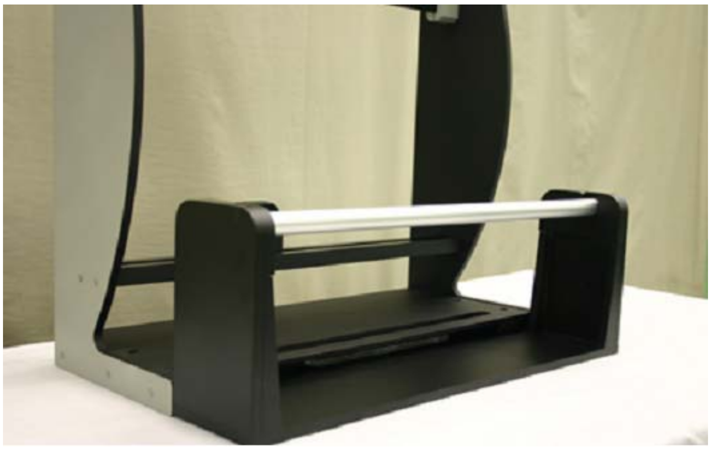
Apart from general requirements such as size of the apparatus; choice of materials; rigidity; etc, when carrying out the design there were items which needed special consideration and investigation to meet the test criteria and to suit the test protocol.

### 3.3.1 Specimen Holders

Two test specimen holders were designed to hold a test specimen in a reproducible test position and to allow for a smooth flow of the yarn specimen from its package. The first specimen holder was designed to hold yarn packages such as a cop or small cone with a maximum diameter of 50mm (Figure 3.3a). The second specimen holder was designed to hold larger yarn packages such as cones with a maximum diameter of 300mm (Figure 3.3b). According to the ASTM Standard D 1423-02 and the British Standard 2085: 1973 for determining twist in yarns by direct counting, withdrawal of yarn over the end of a package adds twist to a yarn, whereas withdrawal from the side of the package does not. Primentas (2003e) conducted a simple experiment to investigate the effect of the yarn unwinding method on yarn twist and twist liveliness. The results confirmed that the over-end unwinding added some twist but when the assembly was unwound sideways, no alteration in its structure was observed. Primentas (2003e) concluded that over-end unwinding of the yarns from cop packages adds some twist which probably increases slightly the twist liveliness of the yarns. Therefore, the apparatus was designed to allow for the yarn to be drawn from its package sideways in order to minimise the variation of twist in the yarn length when the yarn is unwound. The procedure for drawing off a sample from the specimen, on the package holder and fixing it to the sample holder is shown in Figure 3.4.



**(a) Specimen holder for cops**



**(b) Specimen holder for cones**

**Figure 3.3 Yarn specimen holders**

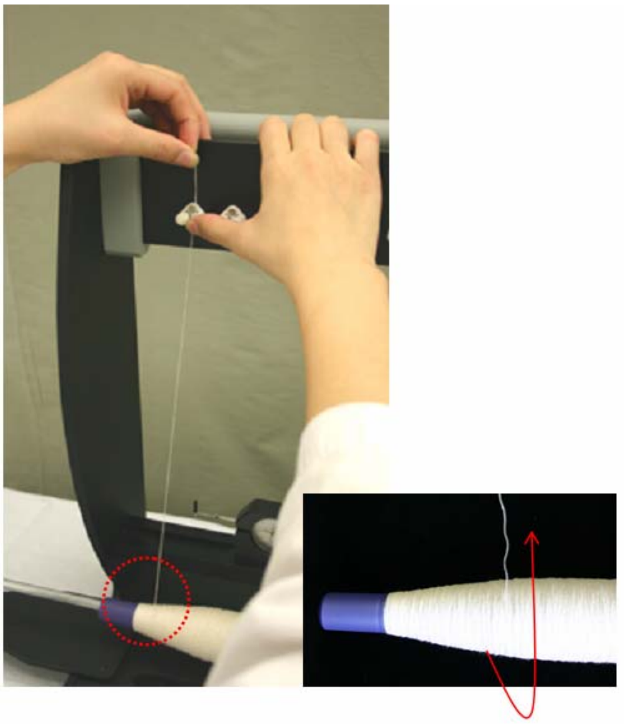


**Figure 3.4 Method for drawing the yarn end from the specimen holder**

### 3.3.2 Pretension Meter

When yarn samples are drawn from their packages, any temporary decrease in tension or introduction of slack will lead to localised deformations that include snarls or kinks. According to Belov et al (2003b) these deformations are a result of stability loss with a transition jump to a new equilibrium state with lower energy. Any stability loss would result in non-uniform lengths of the test samples thus affecting the measured results. Therefore, the test specimen is required to be pretensioned so that the localised deformations can be prevented. To achieve this, the apparatus was designed to allow for a sample to be fed around a pretension meter while the sample is being cut to length.

The pretension meter incorporated into this apparatus shown in Figure 3.5 is an industrial quality instrument. This pretension meter has a range of 0 to 10gf. It is used to bisect the yarn sample to allow for two ends of the yarn to come into close proximity as well as to apply a tension to prevent localised deformations. A modification was needed to allow a yarn sample to be passed around the tension detecting lever and a small rod was attached to the end of the lever. The rod was also designed to be lifted to allow the yarn to be released when a dead weight is hooked on to the lower U-shape portion of the yarn sample.

It was important to recognise, however, that torque in the yarns may be redeveloped or increased by the application of axial tension and investigations are reported later in the chapter to establish the minimum values of tensions needed to prevent localised deformations for all the samples to be tested.

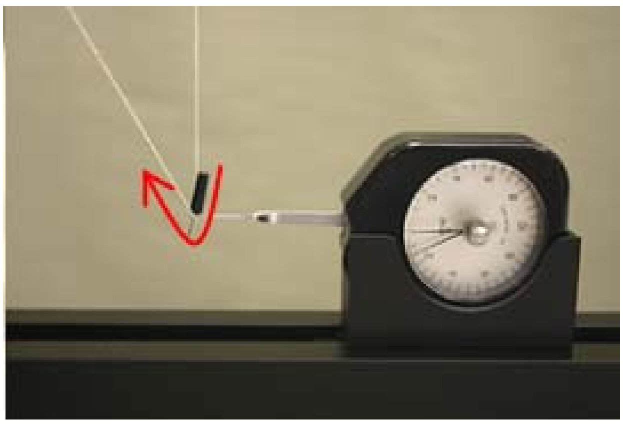


**Figure 3.5 Pretension meter**

### 3.3.3 Sample Holder

The sample holder was designed to hold ten yarn samples at once. Yarn clamps were produced by injection moulding. The configuration of the yarn clamps (Figure 3.6) allows for the yarn ends to be clamped at a maximum distance of 10mm apart by pressing and releasing the spring housing system.

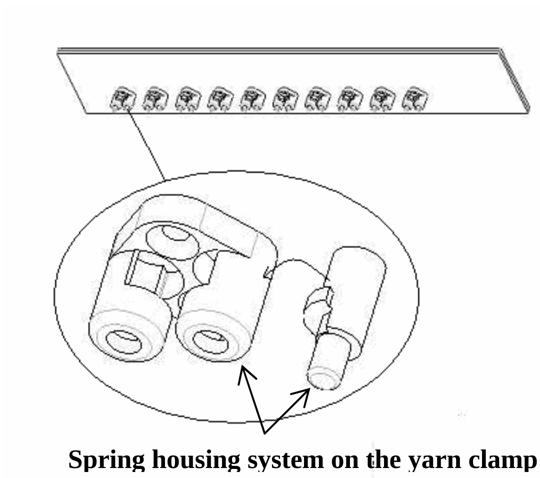



**Figure 3.6 Illustration of the yarn sample holder and yarn clamps**

### 3.3.4 Dead Weights

In this test, it is essential that the samples are fully submerged in the water bath. Most textile fibres are relatively denser than water. For example, natural fibres such as cotton have a specific density of 1.53g/cc, wool has a specific density of 1.32g/cc and manmade fibres such as nylon have a specific density of 1.14g/cc (Morton & Hearle 1986). However, in staple fibre yarns the way the individual fibres are arranged in the yarn cross section or, in other words the fibre packing density in the yarn, determines the amount of air gaps between the fibres and there will be a volume of air within the yarn structure causing the yarns to float Therefore, dead weights were produced from stainless steel to ensure that the samples would sink and be fully submerged in the water.

When the samples are submerged in the water the release of the residual torque is accelerated thus causing a rotation of the yarn. It is evident that the shape of the dead weights might impede or restrict the rate of rotation of the sample and may have an influence on the measured results. To minimize this effect, dead weights were produced from stainless steel thin rods with a hook on one end to allow for the attachment of the weight onto the bottom U-shape loop of the yarn sample. Samples with deadweights attached are shown submerged in the water bath in Figure 3.7.

When testing yarns of different linear densities and fibre content, the weight (in cN/ tex) of the dead weight has to be considered. This is because a yarn with a lower linear density will need a lower dead weight to overcome the buoyant force compared to a yarn with a higher linear density. If the dead weight is greater than necessary the rotation of the sample will be slower. Thus, the minimum mass of the dead weight for different linear densities needed to be investigated and will be reported later in the chapter.

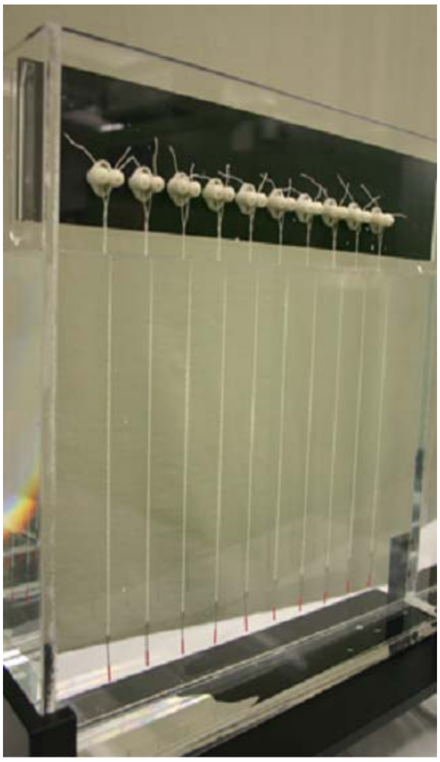


**Figure 3.7 Samples in the water bath**

It should be noted that the scope of this study covers 100% cotton conventional and modified ring spun yarns therefore only the effect of linear density of these types of yarns is considered. The methodology and apparatus should be suitable for other types of yarn but adjustments to parameters may be required. For example, yarns produced from fibres with high elastic properties such as wool or spandex would require a dead weight with a greater mass to straighten the yarn to avoid excessive lengthwise contraction.

### 3.3.5 Twist Tester

In order to count the number of turns accurately, a twist tester is employed. Generally, most textile laboratories are equipped with a twist tester to measure the twist in spun yarns. These instruments can be used in conjunction with the yarn snarling apparatus with only minimal adjustment. A suitable twist tester consists of a pair of clamps, one of which is rotatable in both directions and is connected to a revolution counter. The position of the non-rotatable clamp has to be adjustable to allow for the specified test length of 25cm. Twist testers are either manually rotated by hand or electronically rotated. However, when determining the number of snarls turns removed from a sample accurately, even the electronically driven tester required some manual rotation at the point where there are only a few snarl turns remaining to be counted in the sample. The samples after removal from the water bath are shown in Figure 3.8. Figure 3.9 shows a sample inserted in the twist tester and the number of turns being counted.

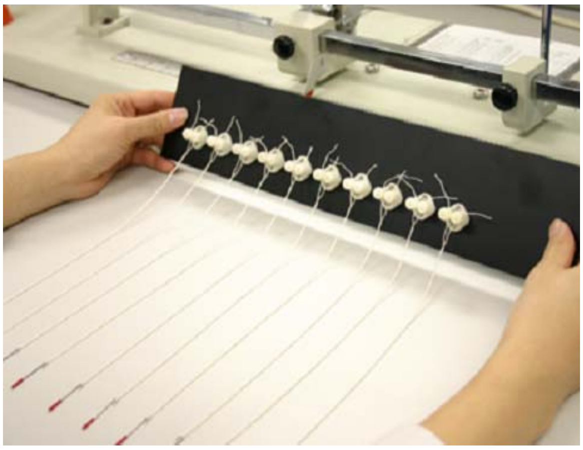


**Figure 3.8 Samples after removal from the water bath**

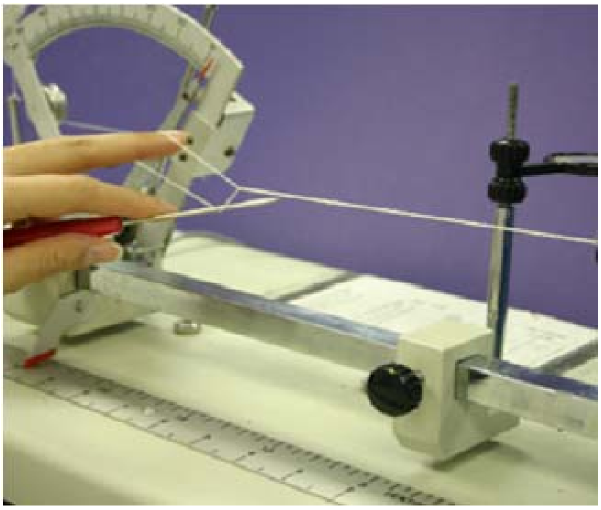


**Figure 3.9 Counting the number of snarl turns on the twist tester**

## 3.4 CONSIDERATION OF TESTING VARIABLES

### 3.4.1 Pretension Determination

#### 3.4.1.1 Experimental

An investigation was carried out to establish the minimum values of pretension needed to prevent localised deformations such as snarls or kinks when preparing the yarn samples. It was decided to produce two cotton singles ring spun yarn specimens of different linear densities as the effect of pretension on a very coarse yarn and a finer yarn could be determined. The reason for choosing cotton as the fibre for the experimental work was because at the time of the experiments, the majority of the developments related to reducing twist liveliness concentrated on 100% cotton yarns, for example the Nu-Torque system. However, it should be noted that if yarns containing different fibres were to be tested, further experiments would have to be conducted due to the difference in the fibre properties. The conventional ring spun yarn specimens were spun on a six spindle spin tester. The details of the yarn specimens are shown in Table 3.1.

**Table 3.1 Details of the yarn specimens**

| Specimen no. | Yarn Count Ne | Yarn Count Tex | Twist Multiple (TPM) | Roving Quality |
|---|---|---|---|---|
| **1** | **7** | 84.36 | **4.20** (437) | 100% Carded Cotton, Micronaire Value 4.00<br>Fibre Length 28.7mm |
| **2** | **20** | 29.53 | **3.60** (634) | 100% Combed Cotton, Micronaire Value 4.29<br>Fibre Length 30mm |

The two yarn specimens were tested using the developed yarn snarling apparatus and method as described in Section 3.2.3 of this Chapter. For each yarn specimen, thirty tests were carried out; the dead weight was fixed at 0.003cN/tex and the pretensions used are outlined in Table 3.2

**Table 3.2 List of pretensions**

| Pretension cN/tex | Specimen 1 7Ne (84.4tex) | | Pretension cN/tex | Specimen 2 20Ne (29.5tex) | |
|---|---|---|---|---|---|
| | cN | g | | cN | g |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.060 | 5.061 | 5.163 | 0.060 | 1.772 | 1.806 |
| 0.120 | 10.128 | 10.330 | 0.300 | 8.868 | 9.035 |

**3.4.1.2. Results and discussion**

The mean values of the number of snarl turns for the two yarn specimens with varying pretensions are plotted in Figure 3.10. The results show that the coarser 7Ne yarn had a lower number of snarl turns compared to the finer 20Ne yarn.

The effect of pretension on the number of snarl turns for 20Ne and 7Ne yarns can be seen. It is evident that, for both yarn specimens, an increase in pretension from 0 to 0.06cN/tex results in a decrease in the number of snarl turns. It was observed that, when a higher pretension was applied, a slightly shorter length of yarn sample was measured and consequently a lower value of snarl turns resulted. However, it was found that when using zero pretension, it was very difficult in practice to prepare the yarn samples without any localised deformations along the test length and this observation confirms that a pretension is required when conducting this test.

An unpaired t-test was performed in order to ascertain whether there is a significant difference between using pretensions of 0.06cN/tex and 0.3cN/tex when testing 20Ne yarns. The t-test revealed that there was no significant difference at the $p=0.05$ level between using the different pretensions for testing the 20Ne yarn specimen.

A second unpaired t-test was performed to determine whether there are significant differences between using pretensions of 0.06cN/tex and 0.12cN/tex when testing 7Ne yarns. The t-test revealed that there was no significant difference at the $p=0.05$ level between using the different pretensions when testing the 7Ne yarn specimen.

The results indicate that 0.06cN/tex can be used as the minimum tension for this test as it was found to contribute enough tension so as to remove the localised deformations for a range of yarn counts for ring spun yarns made from cotton.

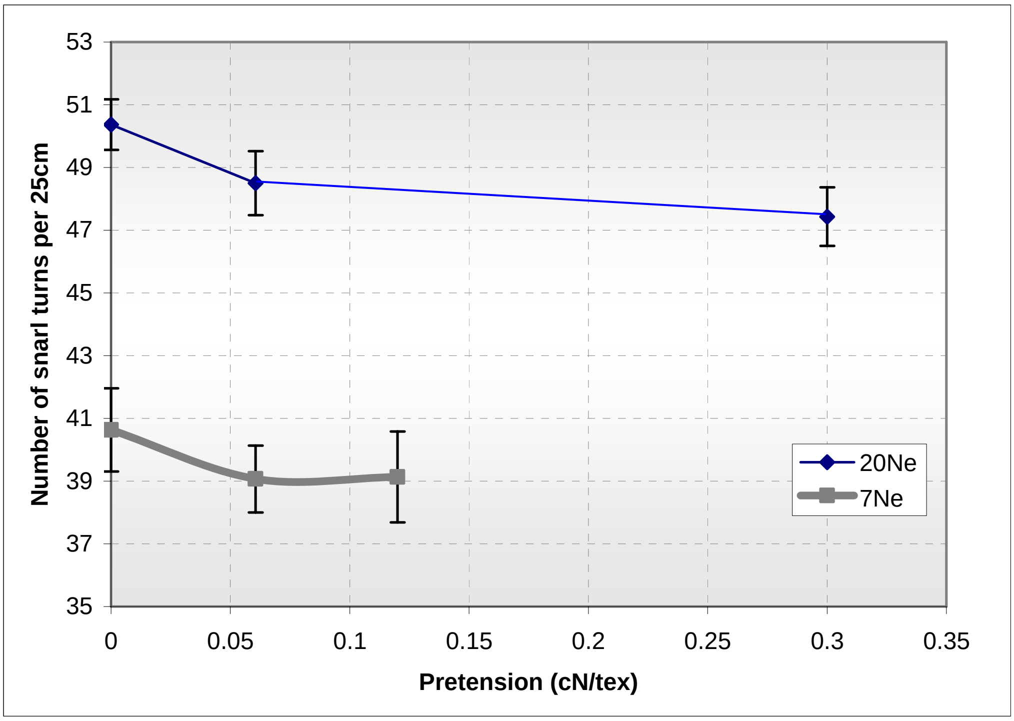



**Figure 3.10 Effect of pretension on the number of snarl turns**

### 3.4.2 Determination of Dead Weights

#### 3.4.2.1 Experimental

An experiment was carried out to investigate the effect of dead weight on the number of snarl turns. It is important to select a correct dead weight which is sufficiently heavy to overcome the buoyancy effects of the yarn in water but light enough so as to ensure that the rotation of the yarn samples is not restricted. The yarn specimens outlined in Table 3.1 were used in this experiment. The two yarn specimens were tested using the developed apparatus and method. For each yarn specimen, thirty tests were carried out.

The pretension was set at 0.06cN/tex and it was decided to use the dead weights as shown in Table 3.3 for the initial experiments.

**Table 3.3 List of dead weights**

| **Dead Weight cN/tex** | **Specimen 1 7Ne (84.4tex)** | | **Specimen 2 20Ne (29.5tex)** | |
|---|---|---|---|---|
| | **cN** | **g** | **cN** | g |
| 0.001 | 0.084 | 0.086 | 0.029 | 0.030 |
| 0.003 | 0.253 | 0.258 | 0.090 | 0.092 |
| 0.005 | 0.422 | 0.430 | 0.148 | 0.151 |
| 0.010 | 0.844 | 0.860 | 0.295 | 0.301 |
| 0.020 | 1.687 | 1.721 | 0.591 | 0.602 |

### 3.4.2.2 Results and discussion

The mean values of the number of snarl turns for the two yarn specimens with varying dead weights are plotted in Figure 3.11. Similar to the pretension experiment, the results show that the 7Ne yarn specimen had a lower number of snarl turns compared to the 20Ne yarn specimen.

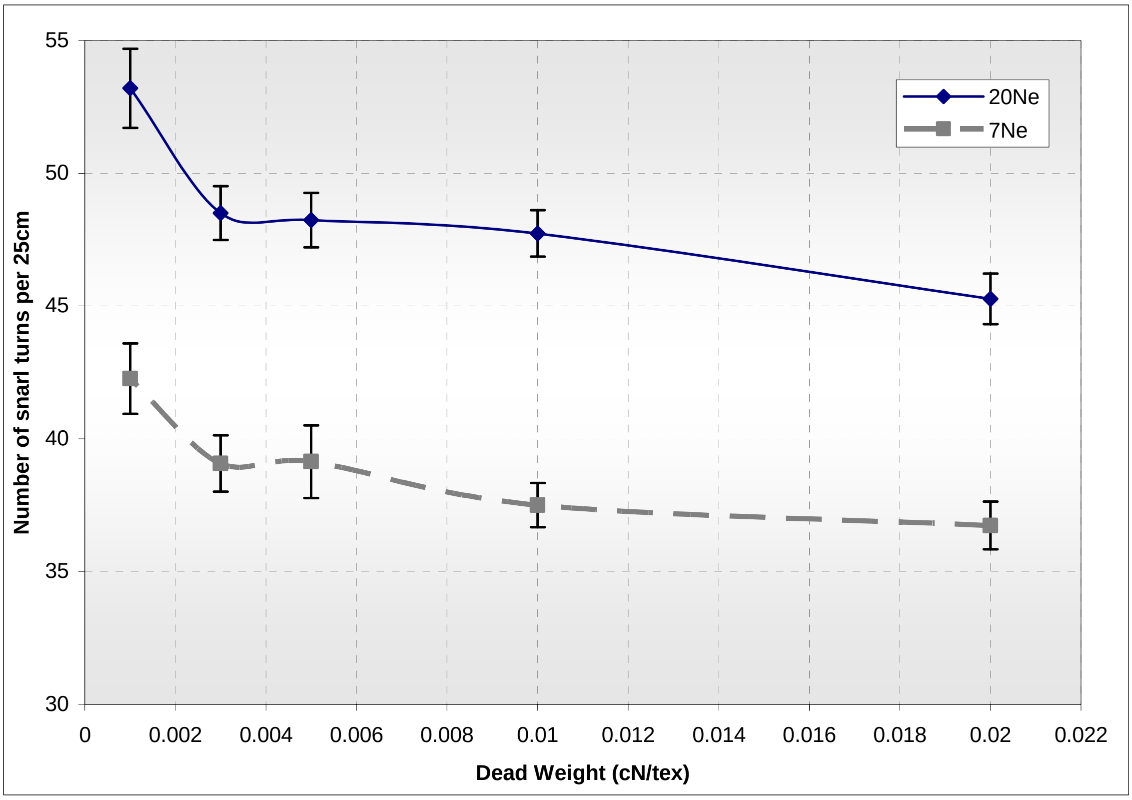



**Figure 3.11 Effect of dead weight on the number of snarl turns**

A one way analysis of variance (ANOVA) was performed in order to determine whether there was significant difference between the means when using different dead weights assuming the observations were independent and normally distributed. An important assumption when using analysis of variance is that all treatments have similar variance therefore a simple check was carried out to confirm that there was equal variance. As shown in Table 3.4 there is a significant difference between using different dead weights for testing the snarl turns of both yarn specimens as the calculated F values exceed the tabulated value of F ($p = 0.001$).

In order to determine if the differences in the snarl turn means for each dead weight were significant, the Newman-Keuls multiple range test was selected because it provides a high degree of protection for the entire null hypothesis. The means in Table 3.5 marked with the same superscripts were not significantly different between each other. The means marked with different superscripts were significantly different between each other at the 0.05 level.

Referring to Table 3.5, the number of snarl turns of the 20Ne yarn specimen using a 0.001cN/tex dead weight was significantly higher than those for the other dead weights at the 0.05 level but it was observed that the yarn samples tended to float on the water surface when using this very light dead weight. Therefore the use of the 0.001cN/tex dead weight for testing 20Ne yarn specimens cannot be considered. The snarl turns of the 20Ne yarn specimens decreased very slightly from 48.5 turns/25cm using 0.003cN/tex dead weight to 48.2 turns/25cm using 0.005cN/tex and then decreased to 47.7 turns/25cm when using 0.01cN/tex. However, there were no significant differences between the means when using these dead weights. The number of snarl turns was significantly smaller than the others when using the 0.02cN/tex dead weight.

Similar to the 20Ne yarn specimen, the number of snarl turns of the 7Ne yarn specimen using a 0.001cN/tex dead weight was significantly higher at the 0.05 level than the other dead weights used. Again, it was observed that the yarn samples tended to float on the water surface when using this dead weight. Therefore, the use of the

0.001cN/tex dead weight for testing this range of yarn counts cannot be considered. The snarl turns of the 7Ne yarn specimen increased very slightly from 39.0 turns/25cm using 0.003cN/tex dead weight to 39.2 turns/25cm using 0.005cN/tex and then decreased to 37.5 turns/25cm and 36.7 turns/25cm when using 0.01cN/tex and 0.02cN/tex respectively. However, there were no significant differences between the means when using these dead weights.

As the difference when using dead weights between 0.003cN/tex and 0.005cN/tex was not significant for both yarn specimens, further work within this dead weight range was conducted to find the minimum dead weight for a range of yarn counts.

**Table 3.4 Analysis of variance for the effect of dead weight on the yarn specimens**

| | | Degrees of Freedom | Sum of Squares | Mean Square | F |
|---|---|---|---|---|---|
| Specimen 1 7Ne (84.4tex) | Between treatments | 4 | 542.77 | 135.69 | 13.84 |
| | Error (within treatments) | 145 | 1421.90 | 9.81 | |
| | Total | 149 | 1964.67 | | |
| Specimen 2 20Ne (29.5tex) | Between treatments | 4 | 994.97 | 248.74 | 26.77 |
| | Error (within treatments) | 145 | 1347.40 | 9.29 | |
| | Total | 149 | 2342.37 | | |

**Table 3.5 Mean number of snarl turns (turns/25cm) for the yarn specimens**

| Yarn specimen | Dead weight (cN/tex) | | | | |
|---|---|---|---|---|---|
| | 0.001 | 0.003 | 0.005 | 0.01 | 0.02 |
| **1 (7Ne, 84.4tex)** | $42.2^{a}$ | $39.0^{b}$ | $39.2^{b}$ | $37.5^{b}$ | $36.7^{b}$ |
| **2 (20Ne, 29.5tex)** | $53.2^{a}$ | $48.5^{b}$ | $48.2^{b}$ | $47.7^{b}$ | $45.2^{c}$ |

*Note: The mean values along the row marked with different superscripts are significantly different from each other at the 0.05 level whereas the mean values with the same superscripts are not significantly different from each other.*

### 3.4.3 Determination of Dead Weights for Different Yarn Counts

#### 3.4.3.1 Experimental

Conventional ring spun yarn specimens were produced on a six spindle Spin Tester. The yarn count, twist multiple and roving used to spin the yarn are shown in Table 3.6 Measurements of the yarn snarling were made on the snarling apparatus using the testing methodology in Section 3.2.3. For each yarn specimen, thirty tests were carried out and the pretension was set at 0.06cN/tex. The dead weights used in the experiment are shown in Table 3.7. As above, it had been established that dead weights based on both 0.003 and 0.005cN/tex produced acceptable results and the tests were conducted using weights calculated from these parameters for each yarn count. As shown in Table 3.7 this resulted in many different weights being required. Therefore, from visual inspection of the figures, some suggested standardised weights were selected as shown in the Table. If confirmed by the testing as producing accurate results, these suggested dead weights would be adopted as standard in the recommended testing procedure.

**Table 3.6 Yarn parameters**

<table>
<tr><th colspan="2">Yarn Count</th><th rowspan="2">Twist Multiple (TPM)</th><th rowspan="2">Roving Quality</th><th rowspan="2">Pretension 0.06cN/tex (g)</th></tr>
<tr><th>Ne</th><th>Tex</th></tr>
<tr><td>7</td><td>84.36</td><td>4.20 (437)</td><td rowspan="2">100% Carded Cotton, Micronaire Value 4.00<br>Fibre Length 28.7mm</td><td>5</td></tr>
<tr><td>10</td><td>59.05</td><td>4.20 (522)</td><td>4</td></tr>
<tr><td>13</td><td>45.42</td><td>4.20 (596)</td><td rowspan="6">100% Combed Cotton, Micronaire Value 4.29<br>Fibre Length 30mm</td><td>3</td></tr>
<tr><td>16</td><td>36.91</td><td>3.50 (551)</td><td rowspan="3">2</td></tr>
<tr><td>18</td><td>32.81</td><td>3.50 (585)</td></tr>
<tr><td>20</td><td>29.53</td><td>3.60 (634)</td></tr>
<tr><td>30</td><td>19.68</td><td>3.65 (787)</td><td rowspan="2">1</td></tr>
<tr><td>40</td><td>14.76</td><td>3.65 (909)</td></tr>
</table>

**Table 3.7 Dead weights used in the testing of each yarn count**

| Yarn Count | | Dead Weights used at 0.003cN/tex (g) | Dead Weights used at 0.005cN/tex (g) | Suggested Standardised Dead Weights used (g) |
|---|---|---|---|---|
| **Ne** | **Tex** | | | |
| **7** | 84.36 | 0.258 | 0.430 | 0.30 |
| **10** | 59.05 | 0.181 | 0.301 | |
| **13** | 45.42 | 0.139 | 0.231 | 0.20 |
| **16** | 36.91 | 0.113 | 0.188 | 0.15 |
| **18** | 32.81 | 0.100 | 0.167 | |
| **20** | 29.53 | 0.092 | 0.151 | 0.10 |
| **30** | 19.68 | 0.060 | 0.100 | |
| **40** | 14.76 | 0.045 | 0.075 | 0.06 |

### 3.4.3.2 Results and discussion

The results when measuring the number of snarl turns for each yarn specimen using the dead weights in Table 3.7 are presented in Table 3.8 It can be seen that, by using the dead weights 0.003cN/tex, 0.005cN/tex and the suggested standardised dead weights for different yarn counts, the snarling results are similar apart from the 40Ne results.

Results of a Newman-Keuls multiple range test on the mean number of snarl turns measured for each yarn count and dead weight in Table 3.8 revealed that there were no significant differences when using the dead weights for each yarn specimen except for 40Ne. The results of the test confirm that there is a significant difference in the mean number of snarl turns for 40Ne when using the 0.003cN/tex dead weight compared to when using the 0.005cN/tex dead weight and the suggested dead weight, but there was no significant difference when using the 0.005cN/tex dead weight and the suggested dead weight. This indicates that finer yarn counts of 40Ne and above may be more sensitive to the increase in dead weight but it should be noted that, in practice, the 0.003cN/tex dead weight for 40Ne is extremely small and great precision is required during the testing procedure.

From this analysis it was found that the suggested dead weights shown in Table 3.7 (between 0.003cN/tex and 0.005cN/tex) for each yarn count could be used as a standard set when testing 100% cotton ring yarns.

**Table 3.8 Mean number of snarl turns (turns/25cm) for different yarn counts**

| Yarn count | | Mean number of snarl turns<br>Dead weight (cN/tex) | | |
|---|---|---|---|---|
| **Ne** | **Tex** | 0.003 | 0.005 | Suggested |
| **7** | 84.36 | 39.0 | 39.2 | 38.9 |
| **10** | 59.05 | 47.4 | 46.2 | 46.5 |
| **13** | 45.42 | 55.1 | 53.2 | 52.7 |
| **16** | 36.91 | 49.3 | 46.5 | 46.5 |
| **18** | 32.81 | 51.4 | 49.5 | 49.8 |
| **20** | 29.53 | 48.5 | 48.2 | 47.7 |
| **30** | 19.68 | 69.9 | 70.2 | 69.5 |
| **40** | 14.76 | 78.7[a] | 75.1[b] | 74.9[b] |

*Note: The mean values along the row marked with different superscripts are significantly different from each other at the 0.05 level whereas the mean values with the same superscripts are not significantly different from each other.*

## 3.5 RECOMMENDED TESTING PROTOCOL

After completing the construction and testing of the apparatus and the determination of testing variables, a detailed manual of operation was prepared and is included in Appendix 3.1. A summary of the finalised sequence of operations to instruct an operator in the correct procedure is as follows:

- Condition specimens in a controlled laboratory environment with standard atmospheric conditions (65 ± 2% RH, 20 ± 2$^{o}$C) for at least 24 hours;
- Place the yarn specimen under examination onto the yarn specimen holder;
- Slot the sample holder into the main frame;
- Draw off the specimen sample from the yarn package and clamp the end of the sample with one of the sample holder clamps;
- Draw the free end of the sample around the pretension meter before clamping it in the second sample holder clamp;
- Adjust length of the sample by reading the amount of tension applied on the pretension meter so as to remove any local deformations that may occur such as snarls or kinks;
- Place the recommended deadweight at the point where the sample is looped around the pretension meter;

- Once ten samples have been prepared, remove the sample holder from the main frame and slot it into the top of the water bath so that the samples are submerged;
- Sufficient time to be allowed for the yarn to reach the maximum snarling potential i.e. no rotational movement (approximately 3 minutes);
- After removal from the water bath position the samples near a twist tester;
- Untwist the yarn samples by the twist tester until no snarls remain;
- Finally, record the number of snarl turns that have been untwisted from a 25cm length of sample.

## 3.6 EVALUATION OF THE APPARATUS AND METHOLODOLOGY

The true accuracy or precision of a test can only be evaluated by repeated testing of identical material both within the same laboratory (intra-laboratory) and between different laboratories (inter-laboratory). There are two measurement concepts that are used to express precision in the evaluation of a test method. They are commonly referred to as 'repeatability' and 'reproducibility' (ASTM Standard E 691-05; British Standard 5532: Part 1:1978).

The measurements of repeatability and reproducibility determine the proportion of measurement variability that is due to:

- The items or parts being measured (part to part variation).
- The operator of the gages or measurement system (reproducibility).
- Errors in the measurements over several trials by the same operators of the same parts (repeatability).

In the ideal case, all variability in measurements should be due to the part to part variation, and only a negligible proportion of the variability should be due to operator reproducibility and trial to trial repeatability (Saville 1999).

### 3.6.1 Experimental

A standard procedure (ASTM Standard E 691-05) was followed for determining the precision of the Yarn Snarling Apparatus and test procedure.

#### 3.6.1.1 Laboratories

According to the ASTM Standard a laboratory is qualified to participate in the study if it contains proper laboratory facilities and testing equipment, competent operators, familiarity with the test method, a reputation for reliable testing work and sufficient time and interest to do a good job. If a laboratory meets all the other requirements, but is not familiar with the test method, the operator(s) in that laboratory should be given an opportunity to become familiarised with the test method and to practice its application before the study begins.

For the intra-laboratory study, the control laboratory in the Institute of Textile and Clothing, The Hong Kong Polytechnic University was used. Four operators were employed. One operator was experienced with the test apparatus and procedure whilst the others were not. Three commercial laboratories namely Intertek Testing Services Hong Kong Ltd. (**ITS**), SGS Hong Kong Ltd. (**SGS**) and Specialised Technology Resources Hong Kong Ltd. (**STR**) participated in the inter-laboratory study. Each laboratory provided two operators to partake in the study. None of the operators were experienced with the test apparatus and procedure.

In order to familiarise the operators with the test apparatus and procedure, detailed instructions on the sample preparation, the conditions of testing, the procedure of the test, and the expression of the test results were provided. In addition, sufficient training was given.

#### 3.6.1.2 Specimens

Five yarn specimens were selected for this study and the details of the specimens are shown in Table 3.9. It was important to choose specimens with different levels of snarling and the major factor to consider in selecting the specimens is that they needed to represent the total variation for the snarling characteristic being studied.

**Table 3.9 Details of the yarn specimens for the intra and inter-laboratory studies**

| Specimen No. | Yarn Count | | Twist Multiple (TPM) | Roving Quality | Approximate number of snarl turns/25cm |
|---|---|---|---|---|---|
| | Ne | tex | | | |
| **1** | **7**# | 84.4 | **3.20** (333) | 100% Carded Cotton, Micronaire Value 4.00 Fibre Length 28.7mm | ~22 |
| **2** | **7**# | 84.4 | **3.80** (396) | | ~31 |
| **3** | **7*** | 84.4 | **4.20** (437) | | ~39 |
| **4** | **20*** | 29.5 | **3.60** (634) | 100% Combed Cotton, Micronaire Value 4.29 Fibre Length 30mm | ~55 |
| **5** | **20**# | 29.5 | **2.50** (440) | | ~20 |

** Conventional singles ring spun yarns*
*# Nu-Torque singles ring spun yarns*

### 3.6.1.3 Procedure

Each laboratory was provided with the Yarn Snarling Apparatus, a standardised twist tester, the set of the same yarn specimens and a protocol of the study. The protocol explained and specified the procedure for the operators. It was specified that each operator was to measure the snarling properties of the specimens that were numbered 1-5. In addition, each specimen had to be tested twice so that a replicate set of results could be obtained. The testing sequence was as follows: 1, 2, 3, 4, 5, 1, 2, 3, 4, 5.

For each specimen, one sample holder that comprised 10 yarn strands had to be tested each time and the number of snarl turns was to be recorded in the table provided to them. The operative assumptions include that the measuring instrument stays in calibration and the operators use the same method of measurement.

### 3.6.2 Results and Discussion

The results from the intra-laboratory and inter-laboratory studies were analysed by Minitab Statistical Software (2003) using an ANOVA method. The ANOVA table was then used to calculate the variance components namely, Repeatability, Reproducibility and Part to Part. Due to the nature of the test it is not possible for each operator to test the same section of yarn. It is assumed that all the sections of the yarn within the same yarn specimen are identical enough to claim that they are from the same part. Therefore, the data was analysed using a nested design. The model includes the main effects for Operator and Part (Operator), in which the part is nested in the operator. In addition, the number of distinct categories that the measurement system can differentiate within the process data could be calculated by dividing the standard deviation for Parts by the standard deviation for Gage, then multiplying by 1.41. This number represents the number of non-overlapping confidence intervals that will span the range of product variation. If the number of categories is five or more this denotes an acceptable measurement system.

The results extracted from the analysis of variance for the intra-laboratory study are presented in Table 3.10. The F test shows that there is no significant difference between the operators in the same laboratory even at the p=0.001 level. The mean measurements for each operator are shown in Figure 3.12(a) and the small difference between the operators is illustrated by the nearly level line. Similarly, the results from the analysis of variance for the inter-laboratory study in Table 3.11 show that there are no significant differences between the operators from different laboratories. However, the main effects plot for the operators in Figure 3.12(b) shows that the operator 'SGS1' has a slightly higher mean value than the other operators. This may indicate that this operator may require additional training in measurement procedure.

The F test results for the intra and inter-laboratory studies in Tables 3.10 and 3.11 and an illustration of the mean measurements in Figures 3.13(a) and (b) show that there is a significant difference between the parts or yarn specimens. Thus, it can be inferred from these results that the measurement system can adequately distinguish between the different levels of snarl turns for the different types of yarns submitted for testing.

**Table 3.10 Analysis of variance for the intra-laboratory study**

| | Degrees of Freedom | Sum of Squares | Mean Square | F | P |
|---|---|---|---|---|---|
| Operator | 3 | 21.70 | 7.23 | 0.02 | 0.99 |
| Part Number (Operator) | 16 | 4145.20 | 259.08 | 246.73 | 0.00 |
| Repeatability | 20 | 21.00 | 1.05 | | |
| Total | 39 | 4187.90 | | | |

**Table 3.11 Analysis of variance for the inter-laboratory study**

| | Degrees of Freedom | Sum of Squares | Mean Square | F | P |
|---|---|---|---|---|---|
| Operator | 5 | 285.13 | 57.02 | 0.19 | 0.95 |
| Part Number (Operator) | 24 | 6882.80 | 286.78 | 391.06 | 0.00 |
| Repeatability | 30 | 22.00 | 0.73 | | |
| Total | 59 | 7189.93 | | | |

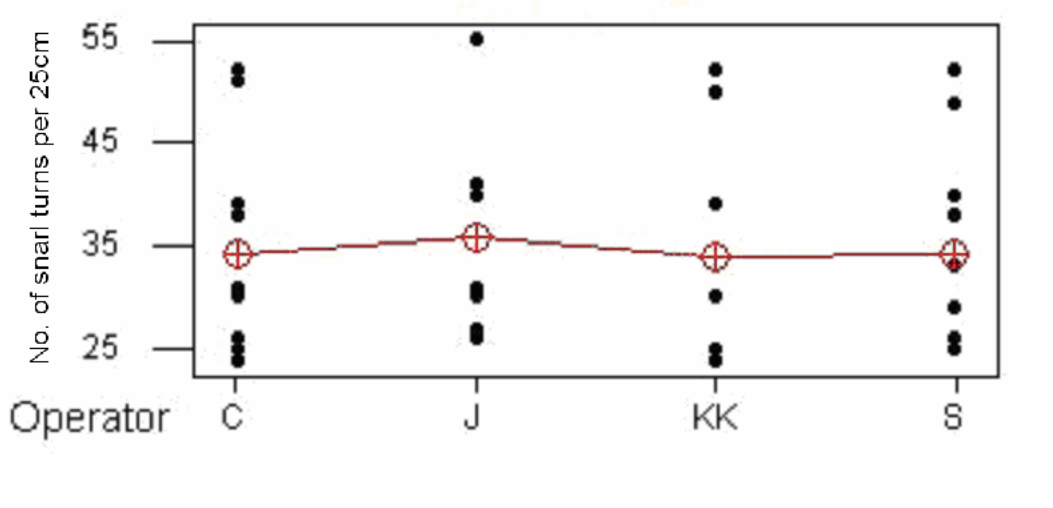
By examining the components of variance for the intra-laboratory study in Table 3.12 the percentage contribution from Part to Part (99.19%) is larger than that of the percentage contributions due to Repeatability or Reproducibility (0.81%). Similarly, it can be seen in Table 3.13 that the percentage contribution from Part to Part in the inter-laboratory study is also larger than the percentage contributions due to Repeatability or Reproducibility. This indicates that most of the variation is due to difference in parts or yarn specimens and very little is due to measurement system error. There are 16 and 20 distinct categories calculated for the intra and inter-laboratory study respectively which confirms that the measurement system can adequately distinguish between differences in the snarl properties of the different types of yarn specimens.

**Table 3.12 Components of variance for the intra-laboratory study**

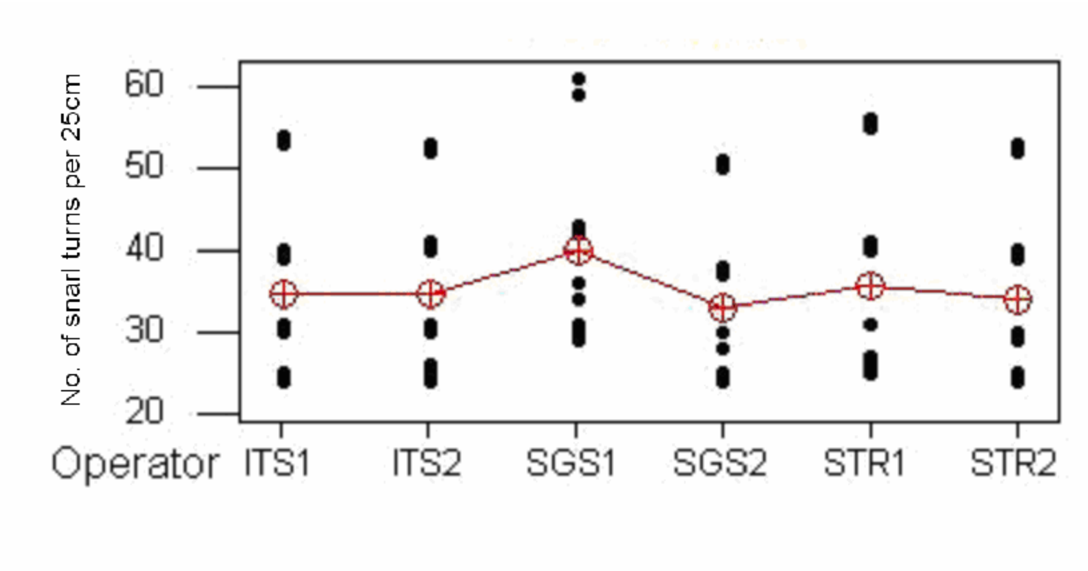
| | Variance | % Contribution | Std Dev (SD) | Study Var (5.15*SD) | % Study Var |
|---|---|---|---|---|---|
| Total Gage | 1.05 | 0.81 | 1.02 | 5.27 | 8.99 |
| Repeatability | 1.05 | 0.81 | 1.02 | 5.27 | 8.99 |
| Reproducibility | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Part to Part | 129.01 | 99.19 | 11.35 | 58.49 | 99.60 |
| Total Variation | 130.06 | 100.00 | 11.40 | 58.73 | 100.00 |
| Number of distinct categories = 16 | | | | | |

**Table 3.13 Components of variance for the inter-laboratory study**

| | Variance | % Contribution | Std Dev (SD) | Study Var (5.15*SD) | % Study Var |
|---|---|---|---|---|---|
| Total Gage | 0.73 | 0.51 | 0.85 | 4.41 | 7.14 |
| Repeatability | 0.73 | 0.51 | 0.85 | 4.41 | 7.14 |
| Reproducibility | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Part to Part | 143.02 | 99.49 | 11.95 | 61.59 | 99.74 |
| Total Variation | 143.75 | 100.00 | 11.98 | 61.74 | 100.00 |
| Number of distinct categories = 20 | | | | | |

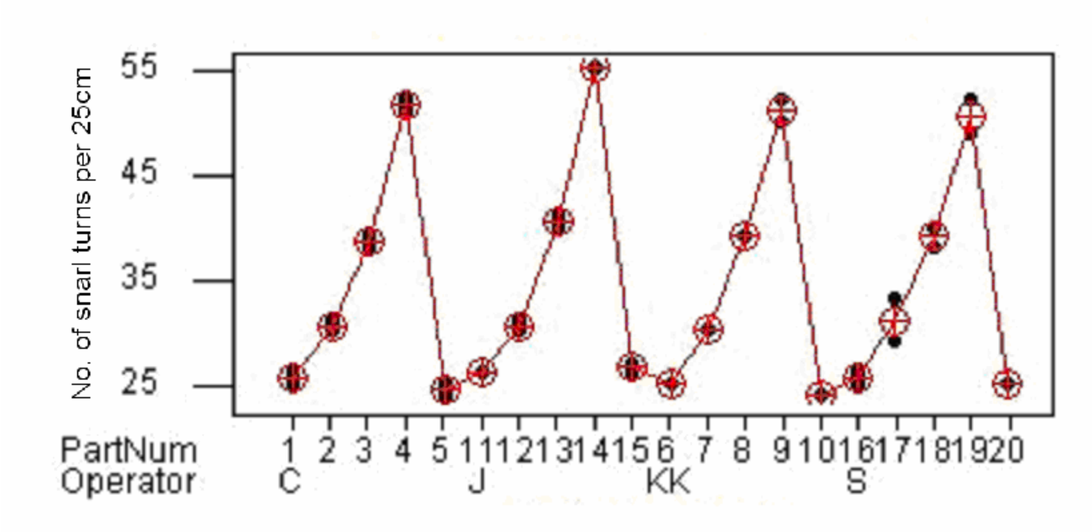



**(a) Intra-laboratory study**

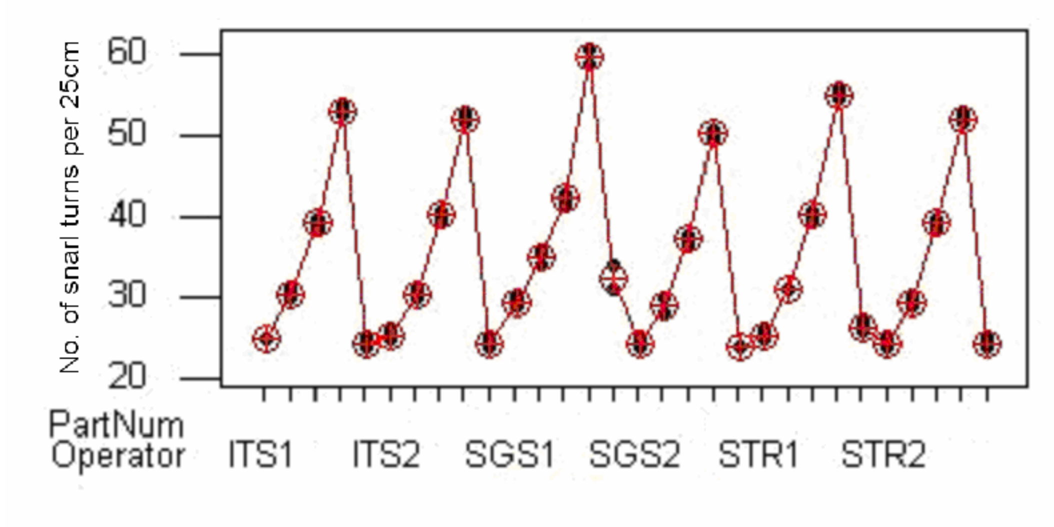



**(b) Inter-laboratory study**

**Figure 3.12 Comparison of the mean measurements for each operator**




**(a) Intra-laboratory study**




**(b) Inter-laboratory study**

**Figure 3.13 Comparison of the mean measurements for each part**

This analysis of the intra and inter-laboratory studies confirms that the Yarn Snarling Apparatus and methodology as detailed in the testing protocol are experimentally robust for measuring and analysing the twist liveliness characteristics of spun yarns.

## 3.7 CONCLUSIONS

A new measurement system has been proposed to indirectly measure twist liveliness by the number of snarl turns. The apparatus and procedure were designed to overcome the disadvantages of the previous methods and to meet the requirements for best practices recommended for such testing methodologies. The resultant system is portable and user-friendly. The operation of the system is relatively simple as unskilled operators can be trained in a very short time. The method is relatively fast as several samples can be prepared and tested in quick succession. The involvement of a pretension system ensures that the test length of the samples is consistent as it prevents the formation of localised snarls or kinks along the test length during the sample preparation stage. The use of dead weights ensures that the samples are fully submerged in water to ensure the samples attain a fully relaxed state. A method has been determined to accurately count the number of snarl turns by using a twist tester.

Experiments for the determination of the minimum pretension and dead weight to test 100% cotton ring spun yarns were conducted. The results show that the minimum pretension is 0.06cN/tex. Dead weights between 0.003cN/tex and 0.005cN/tex should be used depending on the type of yarn.

A detailed testing procedure for use of the apparatus and methodology has been prepared and is shown in Appendix 3.1.

Results of intra and inter laboratory studies involving a total of four laboratories is reported and shows that the Yarn Snarling Apparatus and the recommended testing procedure can be used to make accurate and repeatable measurements of snarl turns over a range of yarn counts and it is relatively independent of operator skill in use. The source of the largest variances in the test is attributed to the expected variation in the levels of snarl turns in different yarn specimens, and only a negligible proportion of the variability was due to operator reproducibility and trial to trial repeatability.

The use of this developed measurement system will be applied in subsequent chapters to investigate the twist liveliness characteristics of Nu-Torque yarns in comparison with conventional yarns and in the development of mathematical models to predict fabric spirality from twist liveliness and other factors. In addition, the measurement system will be further developed in Chapter 6 to improve the determination of the snarl turns by using an automated method.

# CHAPTER 4

# EVALUATION OF TWIST LIVELINESS OF A MODIFIED RING SPUN YARN

## 4.1 INTRODUCTION

Nu-Torque$^{(TM)}$ is a modified ring spinning technology developed at The Hong Kong Polytechnic University (Tao & Xu 2005; Tao, Xu & Wong 2006). The low torque of the Nu-Torque yarns is induced by a false twist operation which is achieved by a specially designed modification device and, if necessary, a strain separation unit installed on the ring spinning machine

A significant advantage of Nu-Torque yarns over conventional ring spun yarns is that the yarns have low residual torque and hence a reduced level of twist liveliness whilst still maintaining good yarn properties such as tenacity, hairiness and evenness. Thus, Nu-Torque yarns have the potential to reduce spirality in knitted fabrics and to minimise other problems in downstream processing without the need for steaming or plying as required for conventional yarns.

An important part of the investigations leading to the development of this system was to assess the twist liveliness of the yarn produced. This required devising arrangements to conduct a comprehensive range of accurate measurements. As it had been established that there are no available standard procedures for evaluating twist liveliness, the methodology and apparatus described in Chapter 3 were important and essential tools for the development of the new spinning system and, potentially, for its successful transfer to industry. In this chapter, the focus of the work is to use these tools for the assessment of twist liveliness of the low torque yarns produced by the Nu-Torque system and to compare the results with those of conventional ring spun yarns of the same yarn count. In addition, the in-process capability of the modified system to produce yarns with low twist liveliness is examined through a production trial.

## 4.2 NU-TORQUE SINGLES RING YARN SPINNING SYSTEM

### 4.2.1 The Nu-Torque System

The Nu-Torque spinning system is illustrated in Figure 4.1. It is composed of a false twist device, a transmission assembly and a modified suction unit to suck up the fibre fly. The false twister is installed between the yarn guide and the front roller on a conventional ring spinning machine and a mechanical transmission system is applied to drive the device. The principle of the device can be found elsewhere (Tao & Xu 2005; Yang 2006) however the main aim of this new method is to produce a novel ring yarn structure with low residual torque, i.e. low twist liveliness, and relatively high strength.

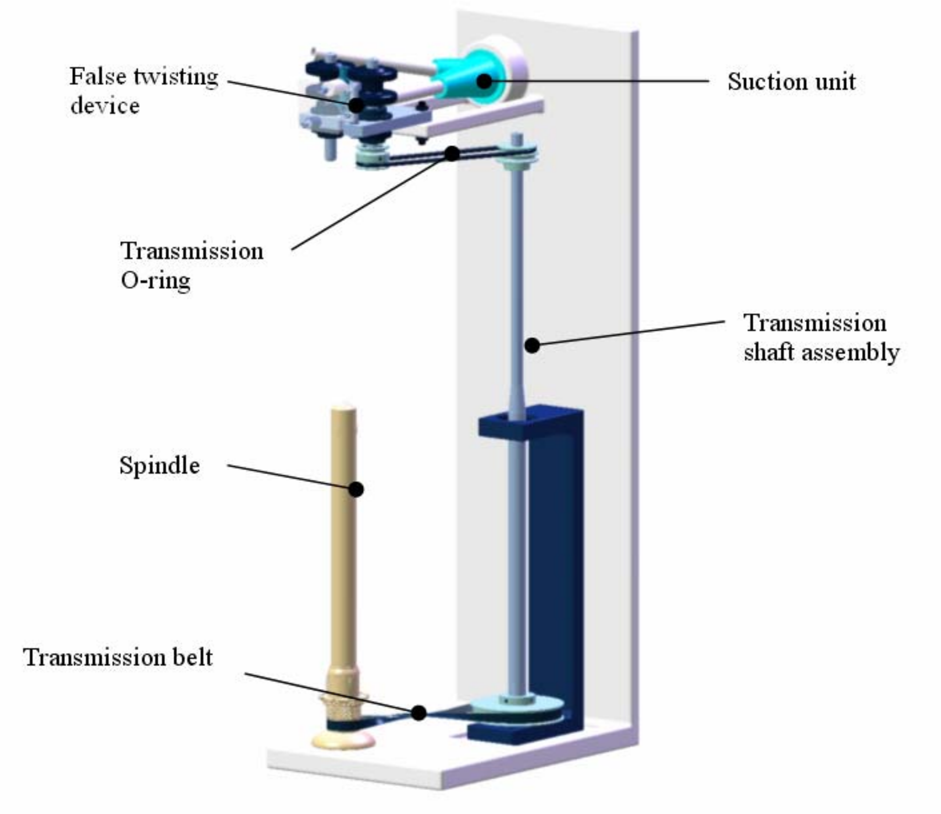



**Figure 4.1 Nu-Torque spinning system**
(Source: Novel Ring Yarns and Production Technology, 2005)

### 4.2.2 Nu-Torque Yarn Structure and Appearance

Analysis by Hua (2007) and Yang (2006) of the yarn structure and appearance of the modified yarn compared to conventional ring spun yarn gave some indications as to how the Nu-Torque yarns can possess lower torque but still retain acceptable tenacity and other yarn properties.

SEM images revealed that low torque ring yarns seem to have a similar appearance to conventional ring yarns but with wrapper-fibre features. The direction of the way the wrapper-fibres are wrapped around the yarn body may help to reduce the yarn torque as it was seen that many of the wrapper fibres were wrapped in the opposite direction to the original twist direction. It was also shown that the low torque yarns had a tighter structure than conventional yarns with normal twist levels. These factors could also explain why hairiness of the Nu-Torque yarns is lower than conventional yarns at similar twist levels.

From tracer fibre analysis, there was evidence that the modified spinning system produces structural modifications that may contribute to the reduction of torque. It was found that the Nu-Torque yarn possesses a different migratory pattern compared to conventional yarns. In addition, segments of the fibre path rotate in different directions inside the yarn so as to counteract the projections of their torque to the yarn axis hence leading to the reduction of yarn residual torque. This effect rarely occurs in conventionally spun yarns.

Analysis of migration behaviour showed that fibres in the low torque yarns were mainly located near the yarn centre whereas in conventionally spun yarns the fibres spread throughout the middle of the yarn cross section. As Tandon, Carnaby, Kim and Choi (1995a) point out, the yarn torque is mainly due to the tensile strains in the outer fibres therefore with fewer fibres in the outer layers the amount of torque would be less. Furthermore, low torque yarns have a higher rate of migration compared with conventional ring yarns.  An increased fibre migration leads to increased transverse movement between layers which reinforces entanglements between fibres and may explain why the tenacity of Nu-Torque yarns can be retained.

Yang (2006) and Hua (2007) conducted Fractional Factorial experiments to identify the key variables that influence the performance of fine and coarse Nu-Torque yarns respectively. It was concluded that the twist multiple and speed ratio (the ratio of the rotational speed between the couple rotors on the false twisting device and the spindle) were the significant factors in determining the yarn twist liveliness as measured using this study's methodology and apparatus. Further experimental work by Yang and Hua using Response Surface Methodology was conducted to find the optimum operating conditions for the Nu-Torque spinning system for several yarn counts between 84.4tex (7Ne) and 19.7tex (30Ne).

Coupled with the reduction of twist level that can reduce the magnitude of the components of torque in a yarn, i.e. fibre bending, torsion and tension, other possible explanations for the lower torque in the Nu-Torque yarns have been explored. Hua (2007) examined the spinning triangle of the modified spinning system and pointed out that the symmetric structure of the spinning triangle can also contribute to the low torque.

## 4.3 COMPARATIVE STUDY OF CONVENTIONAL AND NU-TORQUE SINGLES RING SPUN YARNS

The objective of the Nu-Torque system is to produce a yarn which, compared to conventionally spun yarns, has the advantages of low permanent twist liveliness but without the disadvantages associated with other techniques to reduce twist liveliness such as fibre damage or only temporary reduction in twist liveliness. Therefore, after developing the apparatus and methodology to accurately measure twist liveliness, this study progressed on to conducting investigations into the measured twist liveliness of 29.5tex (20Ne) Nu-Torque yarns in comparison to conventional ring spun yarns with regards to various aspects such as the influence of yarn twist, fibre quality and processes subsequent to spinning. All the yarns were spun on a Zinser 319 ring spinning machine which had 58 spindles with the Nu-Torque modification system installed. The twist liveliness of the yarns was measured using the new methodology and apparatus in accordance with the recommended procedure and 30 readings were taken for each yarn tested as shown in Appendix 4.1. All yarns were conditioned for at least 24 hours prior to testing under standard atmospheric conditions (65 ± 2% RH, 20 ± 2$^{o}$C).

### 4.3.1 Influence of Yarn Twist

In conventional spinning, twist is applied to the fibres by a traveller rotating around a ring flange and the amount of twist inserted in the yarn is controlled by the front roller speed and the traveller rotational speed. The difference between conventional spinning and Nu-Torque spinning is the inclusion of a false twisting device between the front roller and yarn guide as shown in Figure 4.1 and it has been observed that this creates different zones of varying twist above and below the false twisting device (Yang 2006). Results of early investigations have shown that the twist liveliness of conventionally spun yarns exhibits a near linear relationship with the twist or turns per unit length (Banerjee & Alaiban 1988). In Nu-Torque spinning, it is known that the amount of twist inserted in the yarn is also one of the predominant factors correlated with twist liveliness but the relationship had not been established. Therefore, an experiment was conducted to compare the measured twist liveliness of the 29.5tex Nu-Torque and conventional singles ring yarns at different twist levels within the viable spinning range. All the Nu-Torque yarns were spun at a constant speed ratio.

The effect of twist induced by the two spinning systems on the twist liveliness is shown in Figure 4.2. As expected, the Nu-Torque ring spun yarns at all the twist multiples have significantly lower twist liveliness than the conventional ring spun yarn. Moreover, the Nu-Torque yarns can be spun at much lower twist levels than the conventional yarn which cannot be spun at such low levels due to frequent yarn breakage during spinning. There is a good correlation between the twist liveliness and twist for both the conventional (R=0.994) and Nu-Torque (R=0.987) yarns as the correlation coefficients are sufficiently high. This is in agreement with previous studies and verifies that there is a particularly high linear relationship existing between the twist and twist liveliness for the Nu-Torque yarns at a constant speed ratio.

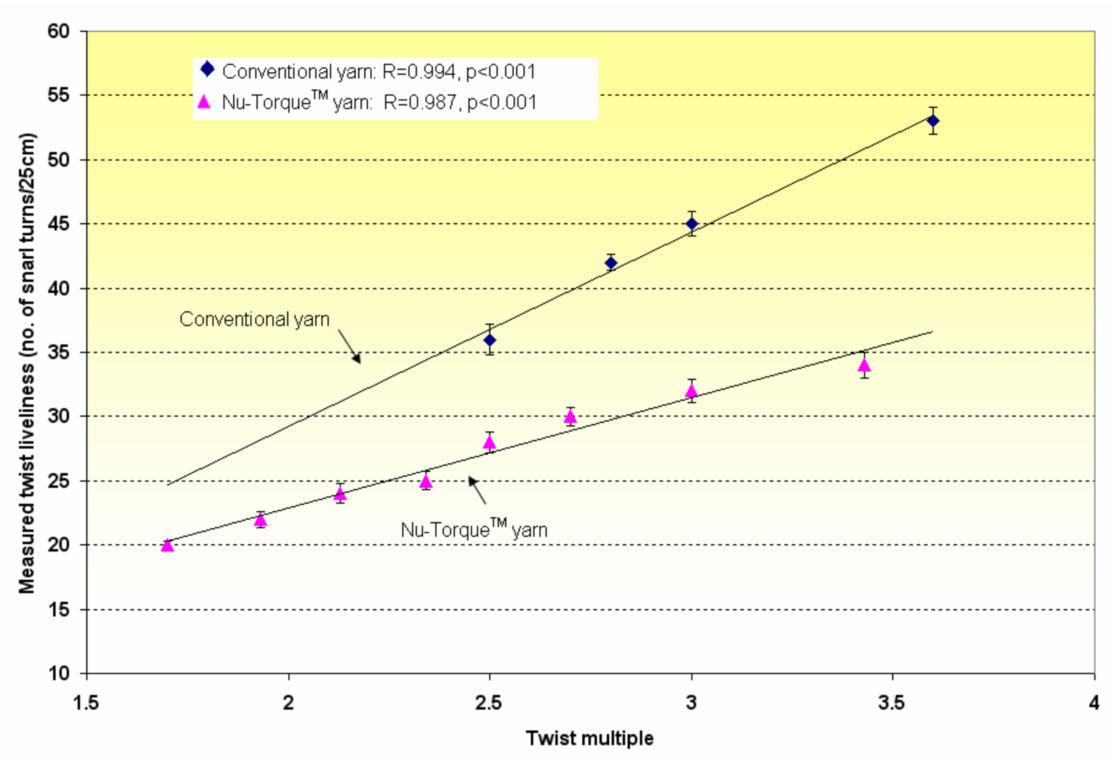



**Figure 4.2 Conventional and Nu-Torque yarn (29.5tex) measured twist liveliness vs twist multiple**

### 4.3.2 Influence of Fibre Quality

Faster production rates are important in industry. In ring spinning, this means increasing the delivery speed by increasing the spindle speed or by reducing the twist. However, a result of increasing the spindle speed is an increase in the height of the spinning triangle and an increase in spinning tension. The spinning triangle is the most important factor influencing yarn quality and ends-down because it affects fibre breakage considerably and adversely influences yarn structure. By increasing the spinning triangle and tension, longer and stronger fibres are required to maintain an acceptable spinning ability and this increases costs as it necessitates using better quality material.

In Nu-Torque spinning it has been observed that the spinning triangle is very similar to that of a highly twisted conventional ring spun yarn where the height of the spinning triangle is reduced (Yang 2006). This means that a potential advantage of the Nu-Torque system is that lower quality or a wider range of fibres could be used to spin yarns with an acceptable spinning ability and yarn quality. Therefore, the influence of different fibre qualities needs to be studied to determine how fibre quality affects the properties of the Nu-Torque yarns.

Previous studies have established that fibres possessing different moduli (tensile, bending and shear) and cross-section shapes lead to different levels of torsional stress induced into the yarn (Lau, Tao & Dhingra 1995). Lord, Mohamed and Ajgaonkar (1978) and De Araujo and Smith (1989a) experimentally determined that, with a higher polyester content in cotton polyester blended yarns, they are more twist lively. However, no studies have been reported on how different cotton fibre properties may affect yarn twist liveliness and an experiment was carried out to compare the measured twist liveliness and different fibre qualities of conventional ring spun yarns with a typical twist multiple of 3.6 and the optimised Nu-Torque yarn with a nominal twist multiple of 2.34 and speed ratio of 0.56. Four different cotton rovings provided by a company were collected for the study. Table 4.1 shows that there was a range of fibre properties, with the Pima cotton having the best all round quality and the American + Australian cotton blend being the worst.

**Table 4.1 Cotton fibre properties**

| | American + Australian | American + Sudan | Ivory coast | Pima |
|---|---|---|---|---|
| Fibre length (inch) | 1.17 | 1.33 | 1.21 | 1.44 |
| Uniformity ratio (%) | 62.50 | 63.90 | 63.50 | 63.70 |
| Fibre strength (g/tex) | 21.50 | 26.20 | 23.00 | 29.80 |
| Elongation (%) | 5.40 | 5.70 | 5.00 | 6.00 |
| Micronaire Value | 4.60 | 4.60 | 3.80 | 4.10 |
| Measured roving count (Ne) | 0.77 | 0.78 | 0.88 | 1.07 |

Figure 4.3 shows that the cotton fibre quality does not have a significant effect on the twist liveliness of both conventional and Nu-Torque ring yarns. This may be as expected because the moduli of the different fibres did not vary sufficiently to have a significant effect on induced torsional stress. Therefore, this result implies that choice of cotton fibre quality will not affect the level of twist liveliness in the yarns produced. This is not to say that the selection of fibre quality in the yarn production is not important as it will have an effect in determining other yarn properties such as yarn strength and hairiness. There are studies that have been directed towards determining the correlation between the various cotton fibre properties and ring spun yarn strength and hairiness. According to the previous works, fibre strength has a direct effect on yarn strength (Hunter & Gee 1982; Cheng 2006) and fibre length and fineness have the most significant effects on the yarn hairiness among the fibre properties (Barella, Castro, Manich, Castellar & Hunter 1987).

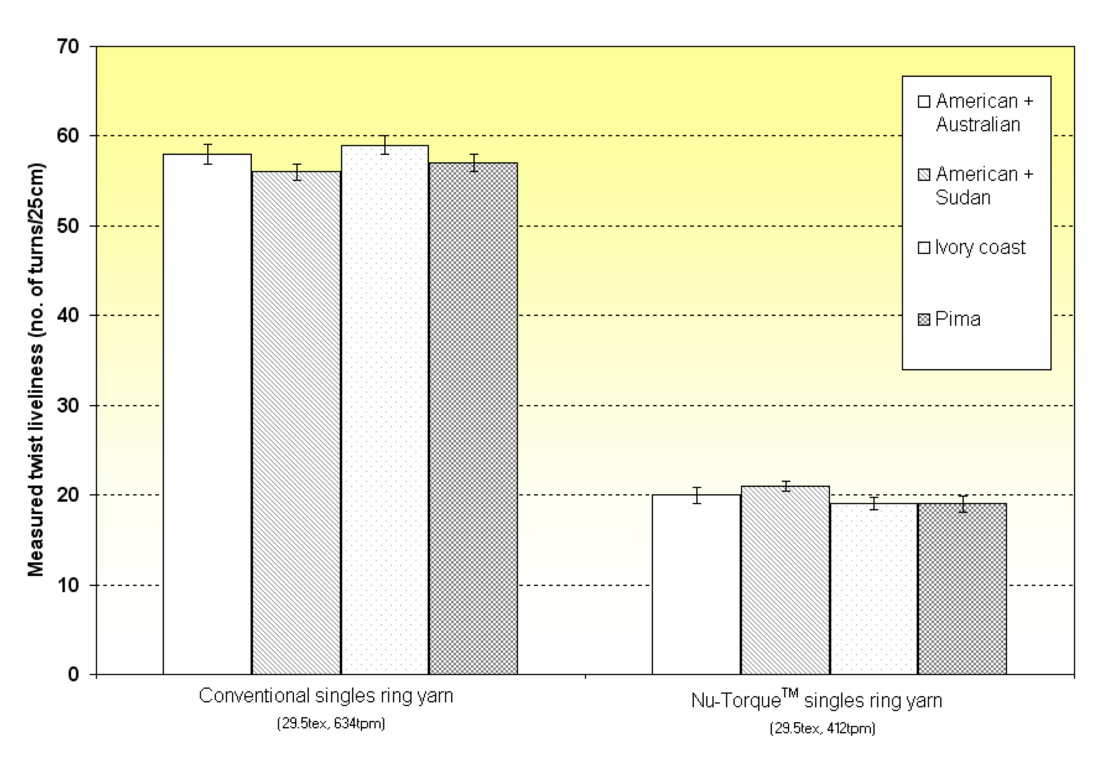



**Figure 4.3 Effect of fibre quality on yarn twist liveliness**

### 4.3.3 Influence of Processes Subsequent to Spinning

After spinning, yarns normally go through several processes before they reach fabric production. Therefore it was considered important to compare the effect of winding, waxing and package dyeing on the twist liveliness of Nu-Torque singles ring yarns in comparison with conventional ring yarns. A conventional ring spun yarn with a typical twist multiple of 3.6 and the optimised Nu-Torque yarn with a twist multiple of 2.34 and speed ratio of 0.56 were spun. The yarns were wound onto cones from cops on a Murata Link Coner No.7-VSS winding machine at 800m/min. For one lot, wax was applied to the yarn by a cylindrical paraffin tube when it was wound onto the cones as wax is normally used in industry to improve the friction resistance of yarns. The unwaxed yarns went on to be package dyed in an industrial setting. At each stage the twist liveliness of the yarns was measured and the results are shown in Figure 4.4.

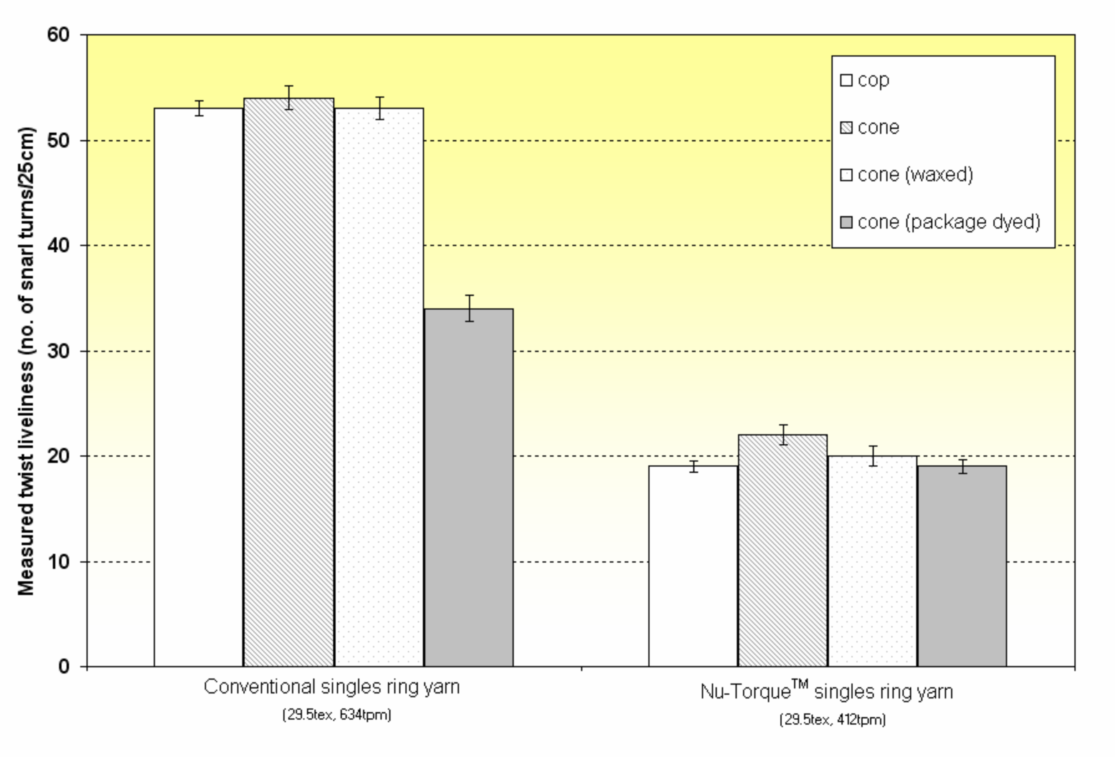



**Figure 4.4 Effect of post-spinning processing on twist liveliness**

The twist liveliness of both the conventional and Nu-torque ring spun yarns increases slightly when the yarn was wound onto a cone from a cop. However, the twist liveliness of the Nu-Torque yarn increased by three snarl turns compared to an increase of one snarl turn for the conventional yarn. The increase in twist liveliness contradicts the findings of Primentas (1995, 2003e) who reported that yarn taken from a cone exhibited a reduced twist liveliness compared to the same yarn taken from a cop. The increase in twist liveliness is probably due to the tension applied to the yarn resulting from the winding speed and tensioning devices on the winding machine rather than the addition of twist when the yarn is withdrawn over the end of the package (ASTM Standard D 1423-02; British Standard 2085: 1973).

With the application of wax during winding, the twist liveliness of both conventional and Nu-Torque yarns was not significantly different from the twist liveliness measured from the yarns on the unwaxed cones as only a reduction of one to two snarl turns was recorded.

Finally, it can be seen that package dyeing significantly reduced the twist liveliness of the conventional yarn but not the twist liveliness of the Nu-Torque yarn. During package dyeing the yarns are subjected to heat and moisture under pressure. It is generally acknowledged (Primentas 1995) that the action of these conditions on the yarns is the temporary suspension of their untwisting tendency due to the rearrangement of the inter-molecular bonds of the fibres. Upon drying, the bonds have the ability to reform under a strain-free condition and will tend to restrain the highly stable original bonds which still support the main stress of the distorted fibres. However, when immersing the package dyed yarns in the water bath during testing, a great number of the bonds including the reformed bonds will be broken. Thus the restraining influence would be removed from the strong stress-bearing bonds and the twist liveliness will increase as the yarn attempts to remove the strain. This could provide a possible explanation for the difference between the twist liveliness of the conventional and Nu-Torque yarns after package dyeing because upon immersion in the water bath during testing, the latent torsional strains recovered in the conventional yarns would be much greater than in the Nu-Torque yarns.

## 4.4 PROCESS CAPABILITY ANALYSIS

It is important to ensure that the operation of the Nu-Torque spinning system is stable and has minimal variability of key parameters in order to successfully transfer this technology to industry. This is achieved by analysing the process capability of the process. Before the capability can be analysed the process must be stable. In other words the prediction of future performance is not possible without a stable process. The steps to carrying out a process capability study can be summarised as:

- Verify the process stability;
- Measure the process capability;
- Compare the actual capability to the desired capability;
- Make a decision about process changes.

The performance of the process can be evaluated using the measured properties of the yarn produced by the process. One of the key parameters of the Nu-Torque system is the twist liveliness of the yarn therefore, in this study, to evaluate the process performance and capability of the Nu-Torque system the twist liveliness was monitored during a production trial. Twenty one spinning lots were spun and, for each lot, four yarns were measured when the process was thought to be stable. The raw data can found in Appendix 4.2 and a summary of the yarn specifications and results are shown Table 4.2. Some primary techniques used in process capability analysis such as control charts, histogram and capability indices were then used to analyse the results.

**Table 4.2 Summary of the yarn specification and results of the production trial**

| | | |
|---|---|---|
| **Yarn specification** | Yarn count | 29.5tex |
| | Roving | 1 3/16" fibre length with a micronaire value of 4.29 |
| | Twist multiple | 2.34 |
| **Machine specification** | Spinning machine | Zinser 319 |
| | Speed ratio | 0.56 |
| | Spindle speed | 10,000 rpm |
| **Measured twist liveliness results (turns/25cm)** | Overall average | 19.345 |
| | Average range | 3.285 |

### 4.4.1 Control Charts

Control charts are normally used to ensure that a process is statistically stable. They are a graphical display of the quality characteristics that have been measured from a sample versus the sample number or time (Barrie Wetherill & Brown 1991; Montgomery 2005) Two main types of control charts are used for variable measurement they include an X bar chart and R chart. The X bar chart controls the process mean and the R chart controls the variance. Control limits are placed on the charts and as long as the points plot within the control limits, the process is assumed to be in control. On the other hand if a point plots outside of the control limits or if all points are within the limits but behave in a non-random manner this could be an indication that the process is out of control.

#### 4.4.1.1 Control chart for the process mean

A control chart for means ( $\overline{X}$ chart) was constructed from the results of the twist liveliness measurements from the production trial. The $\overline{X}$ control chart in Figure 4.5 shows a plot of the mean values from each subgroup. The centre line represents the mean of the subgroups ( $\overline{\overline{X}}$ ) and the boundary lines represent the upper (UCL) and lower (LCL) control limits which were determined by the following equations.

$$UCL = \overline{\overline{X}} + 3\left(\frac{\sigma_x}{\sqrt{n}}\right) \tag{4.1}$$

$$LCL = \overline{\overline{X}} - 3\left(\frac{\sigma_x}{\sqrt{n}}\right) \tag{4.2}$$

where n is the subgroup size and $\sigma_x$ is the Process Sigma, which is calculated using the Subgroup Range or Subgroup Sigma statistic. The two methods of estimation should give similar results for in-control data, but the $\sigma_x$ calculated from the Range method is preferable in establishing preliminary control limits, as it is less sensitive to large outliers. Thus Equation (4.3) gives the $\sigma_x$ by the Range method.

$$\sigma_x = \frac{\overline{R}}{d_2} \tag{4.3}$$

where $\overline{R}$ is the average range and $d_2$ is a function of n which can be found in any statistical quality control book. In this application n = 4, therefore $d_2$ =2.059.

#### 4.4.1.2 Control chart for the process spread

A control chart for the range ($\overline{R}$ chart) was constructed from the results of the twist liveliness measurements from the production trial. In Figure 4.6 of the $\overline{R}$ control chart, the plotted statistic is the range which is defined as:

$$Range_j = MAX[x_1, x_2 ..., x_n] - MIN[x_1, x_2 ..., x_n] \tag{4.4}$$

where $x_1$, $x_2$,… are the n observations in each subgroup

The centre line represents the average range ($\overline{R}$) and as with the $\overline{X}$ control chart the boundary lines represent the upper and lower control limits which were determined by the following equations:

$$UCL = \overline{R}D_4 \tag{4.5}$$

$$LCL = \overline{R}D_3 \tag{4.6}$$

where $D_3$ and $D_4$ are a function of n and are found in any statistical quality control book. In this application n = 4, therefore $D_3$ = 0.29 and $D_4$ =1.93.

#### 4.4.1.3 Interpretation of the control charts

In the interpretation of the charts the method assumes that:

- the data is normally distributed;
- the group sizes are equal;
- all groups are equally weighted;
- the observations are independent.

It can be seen from Figures 4.5 and 4.6 of the $\overline{X}$ and $\overline{R}$ charts that the process is in control as all points are within the control limits and there are no obvious non-random trends of the plotted points.

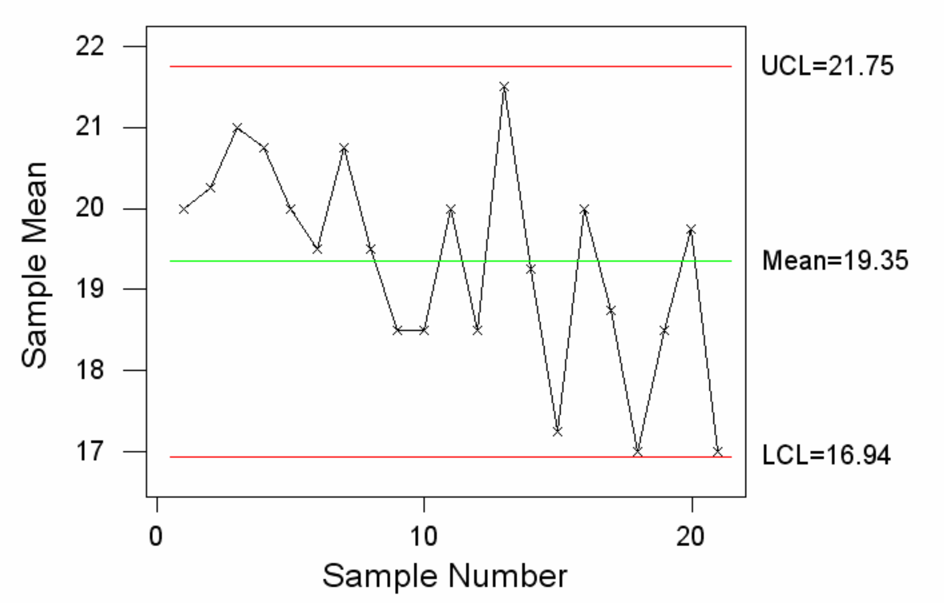



**Figure 4.5** $\overline{X}$ **Chart for the production trial results**

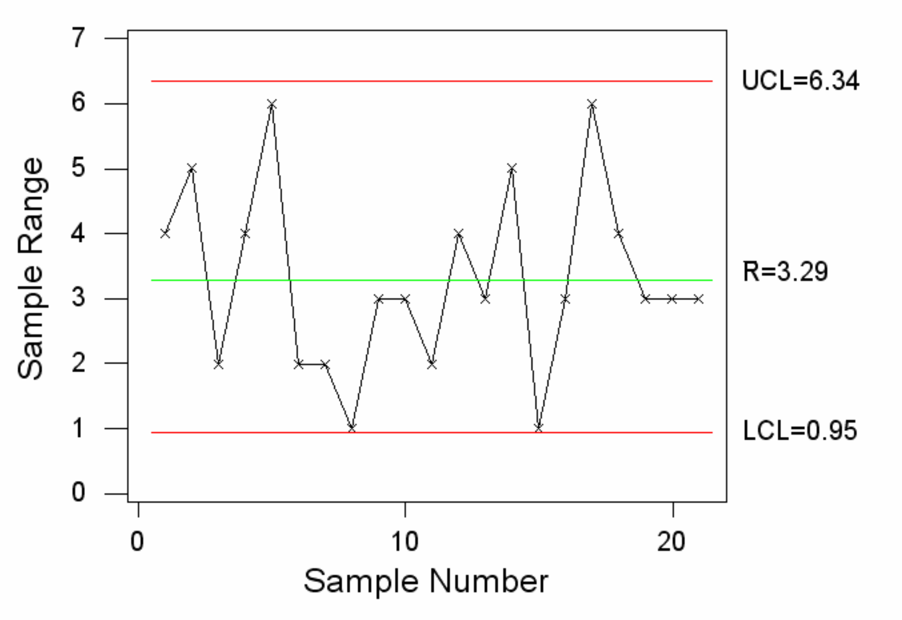



**Figure 4.6** $\overline{R}$ **Chart for the production trial results**

As the process is statistically in control, the next step is to determine if the process is capable, i.e. meeting specification limits, because as described by Polansky and Kirmani (2003, p.625) a manufacturing process can only be as good as its inherent capability of producing a quality product.

### 4.4.2 Histogram

Process capability can be assessed graphically by a histogram. The purpose of a histogram is to take the data that is collected from a process and then display it graphically to view the distribution of the data. From the data, the histogram will show:

- The centre of the data.
- The spread of the data.
- Any data skewness.
- The presence of outliers.
- The presence of multiple modes (or peaks) within the data.

Figure 4.7 shows the histogram of the measurements from the production trial. The histogram shows a count of the data points falling according to the measured twist liveliness. The shape of the histogram implies that the distribution of the twist liveliness measurement is approximately normal. Thus it can be estimated that approximately 99.73% of the yarns manufactured by this process will have a twist liveliness measurement between 15 and 23 turns/25cm.

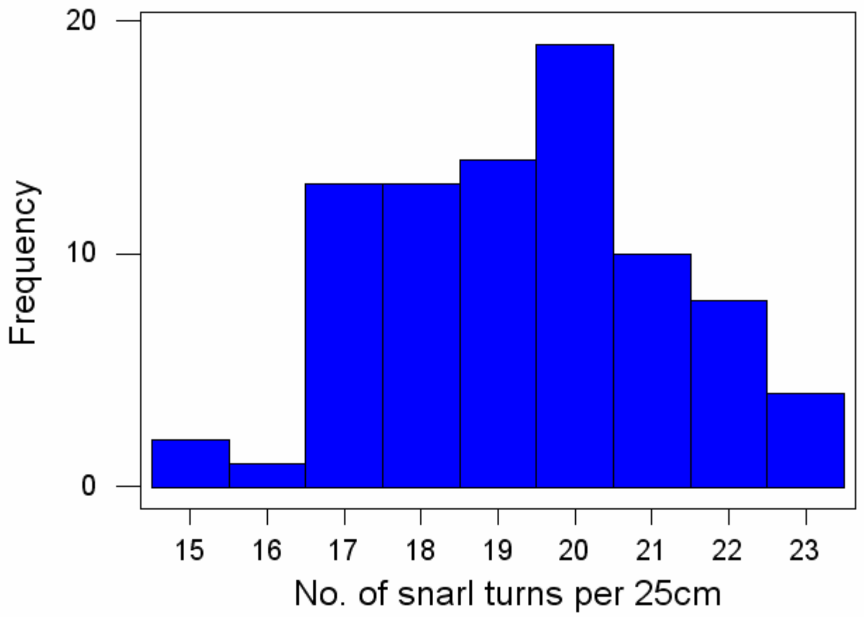



**Figure 4.7 Histogram for the production trial results**

### 4.4.3 Process Capability Ratios

The process capability can be estimated by calculating process capability ratios which are dimensionless measures that quantify the relation between the actual performance of the process and its specified requirements. In general a higher value of the ratio indicates that a lower number of the products are out of the specification. Process capability ratios are based on the assumptions that the process is stable and the studied characteristic is normally distributed. Under these assumptions the two most frequently used indices are $C_p$ in Equation (4.7) which is often called the process capability index and $C_{pk}$ in Equation (4.8) known as the process performance index.

$$C_p = \frac{(USL - LSL)}{6\sigma_w} \tag{4.7}$$

$$C_{pk} = \frac{\min(USL - \mu, \mu - LSL)}{3\sigma_w} \tag{4.8}$$

where, USL and LSL are the upper and lower specification limits respectively, $\mu$ is the process mean and $\sigma_w$ is the process sigma of the in-control process and where the quality characteristic is assumed to be normally distributed.

$C_p$ compares the spread of the observations to the distance between process specifications; the smaller the variability of the process compared to the process specifications, the larger the value of $C_p$ indicating a capable process. $C_{pk}$ also compares natural process variability to process specifications, but takes into account that the process may not be centred. If a process is centred then $C_p = C_{pk}$

However, as the aim of the Nu-Torque system is to reduce the twist liveliness as much as possible, a lower specification limit is not required thus it is a one-sided process. The most well known capability index for a one-sided upper specification is $C_{PU}$ in Equation (4.9) which was introduced by Kane (1986).

$$C_{PU} = \frac{USL - \mu}{3\sigma} \tag{4.9}$$

The upper specification limit for the Nu-Torque process is dependant on the end product produced from the yarn. In this chapter, the Nu-Torque yarn under examination is normally used for multi-feeder circular or flat-bed knitting where the twist liveliness of the yarn will determine the knitting efficiency and fabric quality as discussed in Section 2.2.2. Therefore, a low value for twist liveliness is required. As the upper specification limit for this type of yarn has not been set by any workers until now, an idea of where the limit may be set could be found by examining the work conducted in Chapter 5 of this study. In Figure 5.5, the relationship between the spirality and twist liveliness for various values of tightness factors as predicted by the developed multiple regression model is shown. From this Figure it is possible to get an indication of what the twist liveliness of the yarn should be to achieve an acceptable degree of spirality of $5^o$. If the upper specification limit for twist liveliness is set at 25turns/25cm then the fabric produced by the yarn can still achieve acceptable spirality within the normal range of tightness factors used in industry. The calculated process capability ratio would therefore be $C_{pu}$ = 1.18.

Montgomery (2005, p.336) presents a table with several values of process capability ratios along with the associated values of process fallout, expressed in defective parts or non-conforming units of product per million (ppm). According to the table the estimated fallout for a one sided specification and capability ratio of 1.2 is 159ppm. However, it should be recognised that the calculated process capability ratio in practice is only an estimate which is subject to errors in estimation. Therefore, it is useful to report the estimate of the process capability ratio in terms of a confidence interval. If the quality characteristic follows a normal distribution, then a 95% confidence interval of $C_{pu}$ is determined by:

$$\hat{C}_{pu}\sqrt{\frac{\chi^2_{1-0.025,n-1}}{n-1}} \leq C_{pu} \leq \hat{C}_{pu}\sqrt{\frac{\chi^2_{0.025,n-1}}{n-1}} \qquad (4.10)$$

where $\hat{C}_p$ is the point estimate of $C_{pu}$ and $\chi^2_{1-0.025,n-1}$ and $\chi^2_{0.025,n-1}$ are the percentage points of the chi-square distribution with n-1 degrees of freedom which can be found in any statistical quality control book. From this Equation the derived 95% confidence interval is:

$1.00 \leq C_{pu} \leq 1.36$

The result implies that based on the sample data and a specification limit for twist liveliness of 25turns/25cm, the ratio $C_{pu}$ shows medium relative capability according to Barrie Wetherill and Brown (1991). To improve the capability, it could be investigated whether, by increasing the sample size or by improving the process, the variability of the measured twist liveliness could further be minimised.

## 4.5 CONCLUSIONS

In this chapter, 100% cotton Nu-Torque yarn was compared with conventional ring spun yarn for yarn twist liveliness as measured using the methodology and apparatus developed in Chapter 3. The experiments revealed that Nu-Torque twist liveliness follows the same linear relationship with yarn twist at constant speed ratio as conventional yarn. However the twist liveliness at the same twist level is much lower than for the conventionally spun yarn which is assumed to be due to the structural modifications of the Nu-Torque yarn imposed by the false twisting operation. It was found that different qualities of cotton did not affect the twist liveliness of both conventional and Nu-Torque yarns. This finding indicates the potential of the Nu-Torque system to spin yarns from lower quality cotton with acceptable spinning ability and yarn quality whilst still reducing twist liveliness. This is due to its higher rate of migration and the reduced height of the spinning triangle compared with conventional yarns.

For the 100% cotton Nu-Torque and conventional yarns, an analysis was undertaken to assess changes in twist liveliness resulting from processes downstream to spinning. It was found that the twist liveliness of both the yarns increased slightly when the yarn was wound onto a cone from a cop contradicting a finding from a previous researcher. With the application of wax during winding, the twist liveliness of both conventional and Nu-Torque yarns was not significantly different from the twist liveliness measured in the unwaxed state. Package dyeing significantly reduced the twist liveliness of the conventional yarn but not the twist liveliness of the Nu-Torque yarn. By the introduction of the false twisting operation in the Nu-Torque system the yarn produced has different fibre and yarn configurations compared to the conventionally spun ring yarns and it is these modifications that accounts for the differences in the twist liveliness.

An assessment of the performance and capability of the Nu-Torque system to produce knitting yarns with reduced twist liveliness revealed that during a small scale production trial the system is in control. In addition, the process is estimated to have a medium capability if the upper specification limit for twist liveliness is set at 25turns/25cm indicating good potential for the commercialisation of the Nu-Torque system for producing a novel ring spun yarn.

The apparatus and methodology developed in this study for the measurement of twist liveliness has been extensively applied and played an important role when carrying out an investigation under practical conditions in analysing a modified ring spinning system.

# CHAPTER 5

# MODELS FOR THE PREDICTION OF FABRIC SPIRALITY

## 5.1 INTRODUCTION

Fabric spirality is a complex phenomenon arising from many factors (Lau, Tao & Dhingra 1995). As spirality affects the aesthetics and quality of knitted fabrics, it would be helpful to manufacturers if a predictive model could forecast the degree of fabric spirality accurately. However, predictive models dealing with spirality of cotton fabrics are relatively few in number.

A theoretical approach was used by Hepworth (1993) to study the mechanism by which the use of twist lively yarns leads to spirality in a fabric. A drawback of such theoretical approaches is that they are usually difficult to apply in practice because of the complexities of the models. The models are also usually based on certain idealized assumptions and their success is largely governed by the viability of these assumptions (Fan & Hunter 1998).

Tao J. et al (1997) used a statistical approach for deriving regression equations for the determination of the spirality of cotton single jersey fabrics in terms of yarn linear density, twist factor, fabric tightness factor and loop shape factor. Such an approach is useful to investigate the interdependence of the different factors and to estimate the relative contribution of each factor to the overall degree of fabric spirality. However, in this work the predominant factor causing spirality, the yarn twist liveliness has not been considered.

An alternative to these theoretical and statistical approaches is Artificial Neural Network (ANN) modelling. This is a powerful predictive tool that has been used in many engineering fields to predict material properties. In the textile field alone, many applications have been reported (Mukhopahyay 2002). For example, Babay, Cheikhrouhou, Vermeulen, Rabensolo and Castelain (2004) used statistical and ANN techniques to predict the hairiness of ring spun yarns from cotton fibre properties. Majumdar and Majumdar (2004) used mathematical, statistical and ANN models to predict ring yarn elongation from cotton fibre properties and Beltran, Wang and Wang (2006) used ANN compared with multiple regression to model the relationship between a number of fibre, yarn and fabric properties and the pilling tendency of wool knits. In all the examples it was found that ANN outperformed the traditional approaches. This previous work has demonstrated that ANN can successfully be used for prediction problems in textile applications and thus may similarly be appropriate for predicting the degree of fabric spirality.

In this chapter, the relationship between the degree of fabric spirality and yarn, fabric and knitting machine parameters is examined. Two methods, multiple linear regression and a backpropagation neural network, have been employed to predict fabric spirality from a number of key factors including twist liveliness, which was measured using the methodology and apparatus proposed in this study. A statistical analysis has been undertaken to check the validity of these methods in predicting spirality and to compare the results obtained from the two types of models.

## 5.2 THE APPROACH TO THE DEVELOPMENT OF THE PREDICTIVE MODELS

The two models developed to predict fabric spirality, one based on traditional statistical concepts and the other an Artificial Neural Network (ANN) model, used the same data inputs for their development. Both types of models are generally considered valid for the purpose but a comparison between the two would allow for the best type of model to be selected. However it was anticipated that the ANN model would probably produce superior results because of its ability to represent both linear and non-linear relationships.

The procedure for the development of the models was as follows:

- Data collection and preparation.
- A preliminary analysis of the data.
- Examination of the variables in order to denote statistically the importance of each

variable and to provide transparency and an indication as to the likely validity of the results of the models. Bivariate correlations were calculated to show the inter-relationships between each of the variables. Partial correlations were also calculated between the dependent variable, spirality, and each of the independent variables in turn so as to isolate the specific effect of each variable while controlling for the effects of the other variables.

- Development of a multiple regression model to predict the value of the dependent variable, spirality, by modelling a regression equation to determine the relationship with relevant multiple independent variables.
- Development of an ANN model which is an information processing tool that is inspired by the way biological neural networks in the human brain process information (Fausett 1994). One of the most important characteristics taken from the biological systems is that neural networks learn by example, and do not need to be programmed in the conventional sense. Simply put, the basic learning mechanism consists of training the network by presenting real life examples to it. Weighting factors are adapted through training algorithms until they converge to a more or less stable steady state. After learning, the network then tries to produce the desired output from the inputs (Sette, Boullart & Kiekens 1995).
- Analysis of the two models by using out-of-sample testing data and a comparison of the results.

## 5.3 DATA COLLECTION AND PREPARATION

To develop multiple regression and ANN models it is necessary to have input data covering a range of the independent variables and the dependent variable which have been measured or recorded from actual conditions. This is required in order to produce a model which can, in future, generate a predicted value for the dependent variable, in this case the degree of spirality.

As stated before, it is generally accepted that twist liveliness is a major contributor but it is also well known that fabric spirality is a complex phenomenon and that there are various other yarn, fabric and knitting machine parameters apart from twist liveliness that have an influence (Primentas 1995; Tao J. et al 1997; Chen, Au, Yuen & Yeung 2003). Therefore, five additional factors namely tightness factor, the number of feeders on the knitting machine, the machine gauge (needles/inch), the rotational direction of the machine and whether the fabrics had been piece dyed or not were included in this investigation as independent variables.

### 5.3.1 Yarn and Fabric Details

In this work, the data from a total of 60 fabric samples collected for the study were used for the analysis. The fabrics were produced from several types of cotton yarn samples including conventional ring yarns, Nu-Torque ring yarns and plied yarns. The yarn count was limited to 29.5tex and the twist multiples of the conventional and Nu-Torque yarns were from 2205 to 3443 turns $m^{-1}$ $tex^{1/2}$.

All the fabrics were single jersey fabrics but of various tightness factors (12.82 to 17.18 $tex^{1/2}$ $cm^{-1}$) knitted by circular knitting machines rotating both in the clockwise and anti-clockwise directions. The number of feeders included a single feeder, 54 feeders and 90 feeders and the gauges of the machines were 20, 22 and 24npi. Some of the fabrics were then piece-dyed in the tubular form. The data was randomly divided into forty eight and twelve sets of data that were used for training and evaluating the performance of the predictive models respectively.

### 5.3.2 Measuring Twist Liveliness

The yarn samples from cones were measured for twist liveliness using the testing methodology and apparatus as reported in Chapter 3 and 30 readings were taken for each yarn tested. In the measurements, the twist liveliness was recorded as a positive value if the yarn snarled in the S direction and negative if the yarn snarled in the Z direction.

All yarns were conditioned for at least 24 hours prior to testing under standard atmospheric conditions (65 ± 2% RH, 20 ± 2$^{o}$C).

### 5.3.3 Measuring Knitted Fabric Spirality

Before undertaking any measurements of the samples, the fabrics were placed on a flat surface for at least 48 hours in standard atmospheric conditions of 20 ± 2°C and 65 ± 2% relative humidity (dry relaxed fabrics). All fabrics were then subjected to wash and dry relaxation treatment consisting of three 3A cycles of laundering and tumble drying. The washing temperature and drying temperatures were 60$^o$c and 65$^o$c respectively. After wash and dry relaxation treatment, the dried fabrics were again conditioned at standard atmospheric conditions for 24 hours (wash and dry relaxed fabrics).

A modified IWS test method TM276 was used to measure the angle of spirality in two stages, firstly in the dry relaxed state and secondly after the washing and drying procedure. The angle between the wale line and the line parallel to the machine running direction was measured; in this case, the edge of the circular fabric as shown in Figure 5.1. The angle of spirality θ was calculated using the following Equation:

$$\tan\Theta = \frac{W - W_1}{L_1} \qquad (5.1)$$

As can be seen, four measurements were taken for each fabric sample by substituting $W_1$ with $W_2$, $W_3$ and $W_4$ and $L_1$ with $L_1 + L_2$, $L_1 + L_2 + L_3$ and $L_1 + L_2 + L_3 + L_4$ in the equation. The spirality angle for each sample was taken as the mean of the four measurements. The degree of spirality was recorded as a positive value for the case of Z direction spirality and a negative value for S direction spirality.

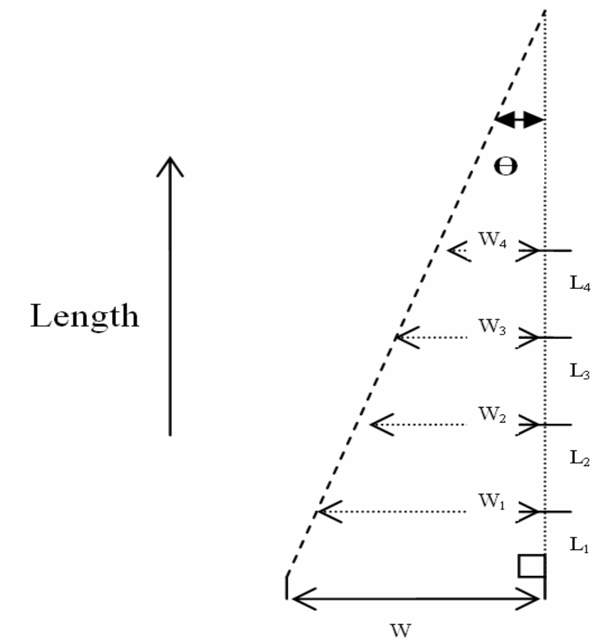



**Figure 5.1 Technique for measuring fabric spirality**

### 5.3.4 Range of Input Variables for Model Development

From the measured testing results and relevant parameters, the ranges of the variables used in the models are in provided in Table 5.1.

For the discrete parameters, the different levels are defined as follows:

- Piece-dyed: 0 = no, 1 = yes
- No. of feeders: 1 = 1 feeder, 2 = 54 feeders, 3 = 90 feeders
- Gauge: 1 = 20 gauge, 2 = 22 gauge, 3 = 24 gauge
- Rotational direction: 0 = clockwise, 1 = anti-clockwise

**Table 5.1 Range of variables**

| Input parameters | Min | Max |
|---|---|---|
| **Yarn and fabric parameters** | | |
| Yarn twist liveliness | **-17** | **61** |
| Tightness factor | **12.82** | **17.18** |
| Piece-dyed | **0** | **1** |
| **Knitting machine parameters:** | | |
| No. of feeders | **1** | **3** |
| Gauge | **1** | **3** |
| Rotational direction | **0** | **1** |
| **Output parameters** | | |
| Degree of spirality (dry relaxed) | **-8.40** | **13.96** |
| Degree of spirality (wash and dry relaxed) | **-3.76** | **26.73** |

## 5.4 PRELIMINARY ANALYSIS

As a preliminary analysis of the data, scatter plots were used to illustrate the correlation of the measured twist liveliness and the angle of spirality as shown in Figures 5.2(a) and 5.2(b) for the dry relaxed and wash and dry relaxed fabrics respectively. In general, it can be seen that if the yarns snarled in the S direction the fabrics spiralled in the Z direction and vice versa. Also as the twist liveliness increased, the angle of spirality increased in both directions. The analysis reveals that the measured twist liveliness is strongly related to the angle of spirality, however the deviations of the experimental points from the best fit line indicate that twist liveliness is not the sole cause of spirality. This confirms that it is necessary to include in the mathematical models the effects of other parameters on fabric spirality.

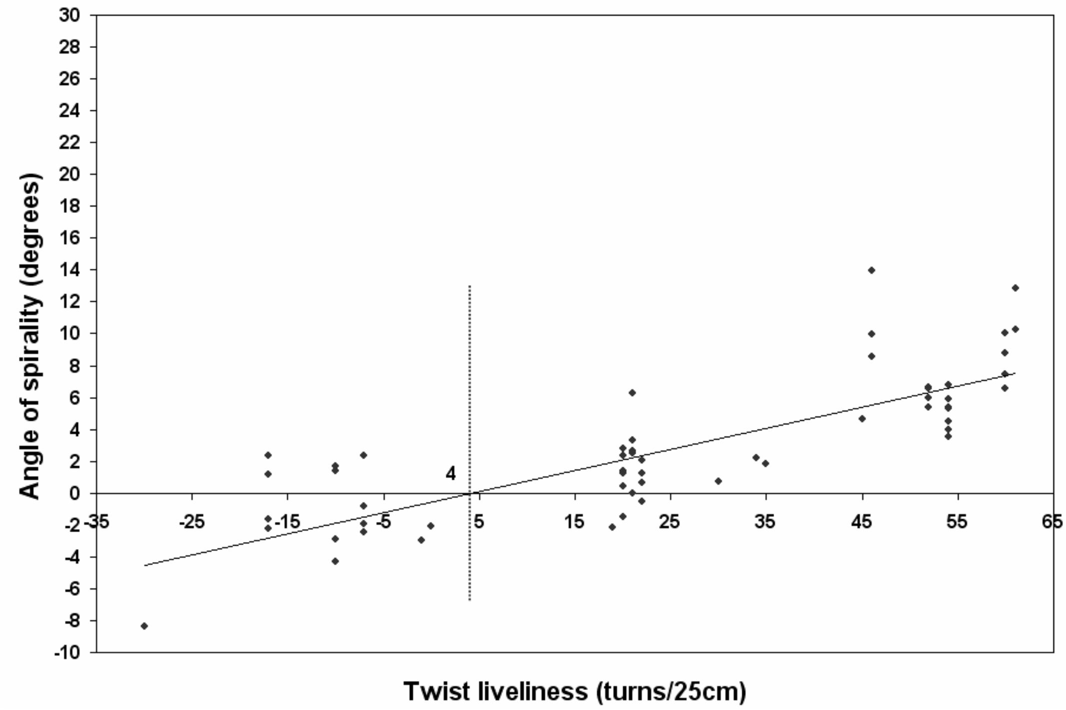



**Figure 5.2(a) Relationship between the measured twist liveliness and angle of spirality of the dry relaxed fabrics**

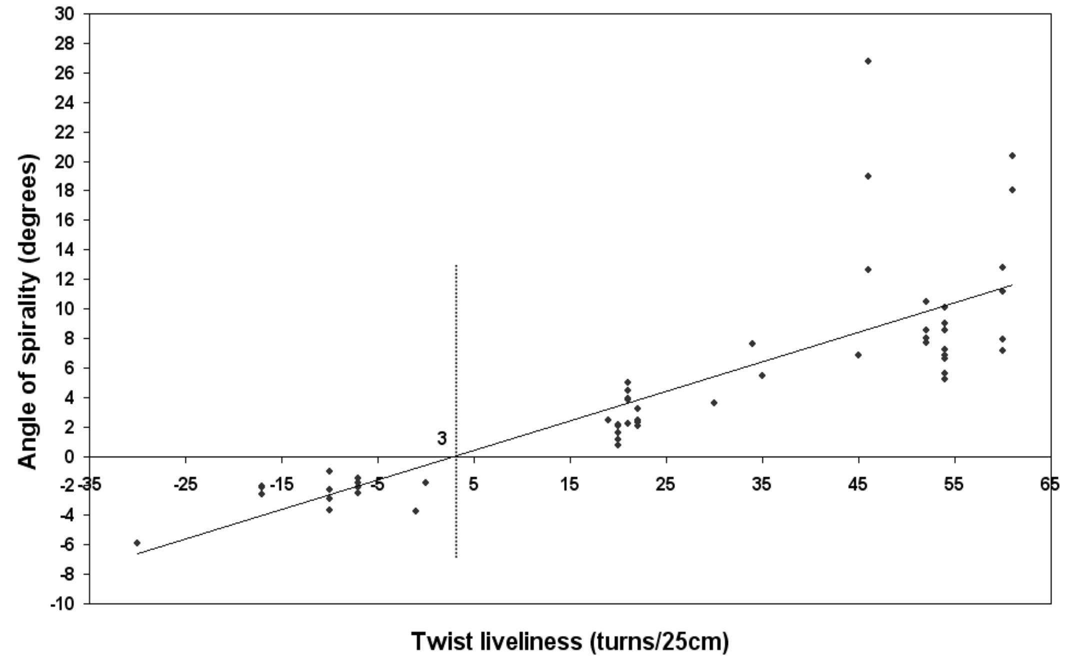



**Figure 5.2(b) Relationship between the measured twist liveliness and angle of spirality of the wash and dry relaxed fabrics**

## 5.5 EXAMINATION OF VARIABLES

For both the dry relaxed and washed and dry relaxed fabrics, the inter-relationships between the angle of spirality and the yarn, fabric and machine variables were analysed by use of the simple (bivariate) and partial correlation coefficients. The computed correlation coefficients are given in Tables 5.2(a) to 5.3(b).

Tables 5.2(a) and 5.2(b) reveal the bivariate correlation coefficients of the dry relaxed and washed and dry relaxed fabric respectively. It can be seen that there are strong positive correlations between the measured twist liveliness and angle of spirality for both the dry relaxed (Pearson correlation value R = 0.807) and wash and dry relaxed fabrics (Pearson correlation value R = 0.795). Tightness factor showed a moderate negative correlation with the angle of spirality for both the dry and wash and dry relaxed fabrics. For the dry relaxed fabrics the effects of the other parameters (number of feeders, gauge, rotational direction and piece dyed) on the angle of spirality were not significant at the 5% level. Whereas, for the wash and dry relaxed fabrics only the number of feeders and gauge showed weak correlations with the angle of spirality.

The method of partial correlation was used to examine the relationship between the angle of spirality and the individual variables when the effects of the other variables are kept constant. Table 5.3(a) presents the partial correlation coefficients of the various variables for the dry relaxed fabrics. It is clear that yarn twist liveliness and tightness factor are the most important variables and are strongly correlated to the angle of spirality. In Table 5.3(b), the partial correlation coefficients of the various variables for the wash and dry relaxed fabrics show that, in addition to twist liveliness and tightness factor, piece dyeing has a correlation with the angle of spirality at the 5% level although it is only a weak correlation.

It is interesting to compare the bivariate and partial correlation coefficients for the wash and dry relaxed fabrics in Tables 5.2(b) and 5.3(b). It can be seen that the strong correlation between the twist liveliness and angle of spirality and the moderate correlation between the angle of spirality and tightness factor become much stronger when the effects of the other variables are kept constant.

It can therefore be confirmed that twist liveliness and tightness factor are the most important parameters influencing fabric spirality whereas the number of feeders, gauge, rotational direction and piece dyeing are less important.

**Table 5.2(a) Simple correlation coefficients between spirality and various variables for dry relaxed fabrics**

| | Angle of spirality | Twist liveliness | Number of feeders | Gauge | Rotational direction | Piece dyed | Tightness Factor |
|---|---|---|---|---|---|---|---|
| **Angle of spirality** | 1 | | | | | | |
| **Twist liveliness** | 0.807 | 1 | | | | | |
| **Number of feeders** | -0.234 (ns) | -0.080 (ns) | 1 | | | | |
| **Gauge** | -0.249 (ns) | -0.109 (ns) | 0.787 | 1 | | | |
| **Rotational direction** | -0.149 (ns) | -0.103 (ns) | -0.235 | 0.056 (ns) | 1 | | |
| **Piece-dyed** | -0.169 (ns) | -0.059 (ns) | 0.370 | 0.358 | -0.091 (ns) | 1 | |
| **Tightness Factor** | -0.522 | -0.202 (ns) | 0.651 | 0.475 | -0.171 (ns) | 0.226 (ns) | 1 |

*ns: not significant at 95% confidence level*

**Table 5.2(b) Simple correlation coefficients between spirality and various variables for wash and dry relaxed fabrics**

| | Angle of spirality | Twist liveliness | Number of feeders | Gauge | Rotational direction | Piece dyed | Tightness Factor |
|---|---|---|---|---|---|---|---|
| | 1 | | | | | | |
| **Twist liveliness** | 0.795 | 1 | | | | | |
| **Number of feeders** | -0.404 | -0.080 (ns) | 1 | | | | |
| **Gauge** | -0.325 | -0.109 (ns) | 0.787 | 1 | | | |
| **Rotational direction** | 0.053 (ns) | -0.103 (ns) | -0.235 (ns) | 0.056 (ns) | 1 | | |
| **Piece-dyed** | -0.248 (ns) | -0.059 (ns) | 0.370 | 0.358 | -0.091 (ns) | 1 | |
| **Tightness Factor** | -0.696 | -0.202 (ns) | 0.010 | 0.475 | -0.171 (ns) | 0.226 (ns) | 1 |

*ns: not significant at 95% confidence level*

**Table 5.3(a) Partial correlation coefficients of various variables for the dry relaxed fabrics**

| | Twist liveliness | Number of feeders | Gauge | Rotational direction | Piece dyed | Tightness Factor |
|---|---|---|---|---|---|---|
| **Angle of spirality** | 0.846 | 0.174 (ns) | -0.050 (ns) | -0.248 (ns) | -0.166 (ns) | -0.628 |

*ns: not significant at 95% confidence level*

**Table 5.3(b) Partial correlation coefficients of various variables for the wash and dry relaxed fabrics**

| | Twist liveliness | Number of feeders | Gauge | Rotational direction | Piece dyed | Tightness Factor |
|---|---|---|---|---|---|---|
| **Angle of spirality** | 0.938 | 0.135 (ns) | 0.007 (ns) | 0.115 (ns) | -0.357 | -0.868 |

*ns: not significant at 95% confidence level*

## 5.6 THE MULTIPLE REGRESSION MODEL

One approach to establishing a quantitative relationship between the angle of spirality and the yarn and fabric variables is to use a multiple regression method on the data. Such an approach can estimate the relative contribution of each variable to the average angle of spirality.

### 5.6.1 Development of the Model

A stepwise multiple regression analysis was first performed to predict the angle of spirality for the dry relaxed fabrics. The analysis was carried out using Minitab statistical software employing a combination of forward selection and backward elimination. The stepwise regression technique inserts or removes variables into a regression model according to the default statistical inclusion criterion (5% level of significance) until a satisfactory regression equation is reached.

For the dry relaxed fabrics the results in Table 5.4(a) reveal that twist liveliness is the most important parameter and accounts for 65% of the variance in the angle of spirality. With the addition of the parameters tightness factor and rotational direction only 81% of the variance in the angle of spirality of the dry relaxed fabric is explained. This implies that the prediction results may not be very accurate if the resultant regression model is used for the dry relaxed fabrics.

A second stepwise multiple regression analysis was performed to predict the angle of spirality for the wash and dry relaxed fabrics as shown in Table 5.4(b). Similar to the dry relaxed fabric, the twist liveliness is the most important parameter that accounts for 63% of the variance in the data. Tightness factor is the other important parameter and together with twist liveliness they account for 93% of the variance in the angle of spirality. The parameter, piece-dyed, did not produce a significant improvement in the variance of spirality (less than 1%) and therefore was not included in the resultant regression equation, which for the angle spirality after wash and dry relaxation, is as given below:

$$Spirality = 68.63 + 0.167T - 4.08TF \qquad (5.2)$$

where the units of spirality, twist liveliness (T) and tightness factor (TF) are degrees, turns/25cm, $tex^{1/2}\ cm^{-1}$, respectively.

**Table 5.4(a) Prediction of fabric spirality (dry relaxed) with an increasing number of yarn, fabric and knitting machine parameters (step-wise method)**

| Step | Factors | Multiple correlation coefficient, R | Percentage variance explained |
|---|---|---|---|
| 1 | Twist liveliness (T) | 0.81 | 65.14 |
| 2 | Tightness Factor (TF) | 0.88 | 78.58 |
| 3 | Rotational direction (R) | 0.89 | 80.56 |

**Table 5.4(b) Prediction of fabric spirality (wash and dry relaxed) with an increasing number of yarn, fabric and knitting machine parameters (step-wise method)**

| Step | Factors | Multiple correlation coefficient, R | Percentage variance explained |
|---|---|---|---|
| 1 | Twist liveliness (T) | 0.79 | 63.12 |
| 2 | Tightness Factor (TF) | 0.96 | 93.04 |
| 3 | Piece-dyed (P) | 0.97 | 93.74 |

### 5.6.2 Assessment of the Model

The prediction accuracy of the multiple regression model can be judged by the regression coefficient of the line that relates the fabric spirality predicted by the model and the actual tested values of the spirality of the fabrics used for training as shown in Figure 5.3. The prediction would be considered good if all data points were aligned on the line of perfect fit whereas the amount of scattering around the line gives an idea of the quality of the modelling. The results show that the predicted values, A, track the measured or actual values, T, very well as the correlation coefficient (R=0.965) is sufficiently high.

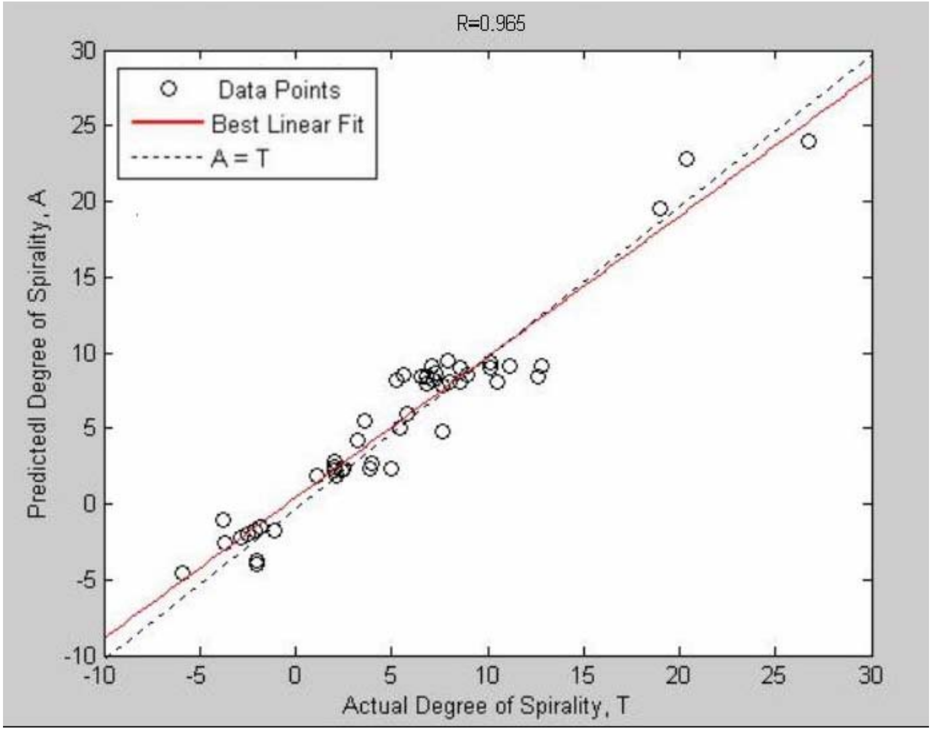



**Figure 5.3 Relationship between the actual and predicted values of spirality for the training set of data (multiple regression model)**

An advantage of a regressional model is the transparency of the effect of the independent variables on the dependent variable. Figure 5.4 shows the combined effect of twist liveliness and tightness factor on the degree of spirality. It is evident that if the tightness factor is increased by one unit, the degree of spirality will decrease by 4 degrees. However, there is negligible effect of on an increase of one snarl turn/25cm on the increase of spirality which is equivalent to approximately 0.2 degrees. One aspect of this study is the consideration of low torque yarns and it is interesting to note that, in practical terms, when considering methods to reduce fabric spirality by producing low torque yarns, the twist liveliness of a yarn has to be reduced by 5 snarl turns/25cm in order to decrease the degree of spirality by 1 degree.

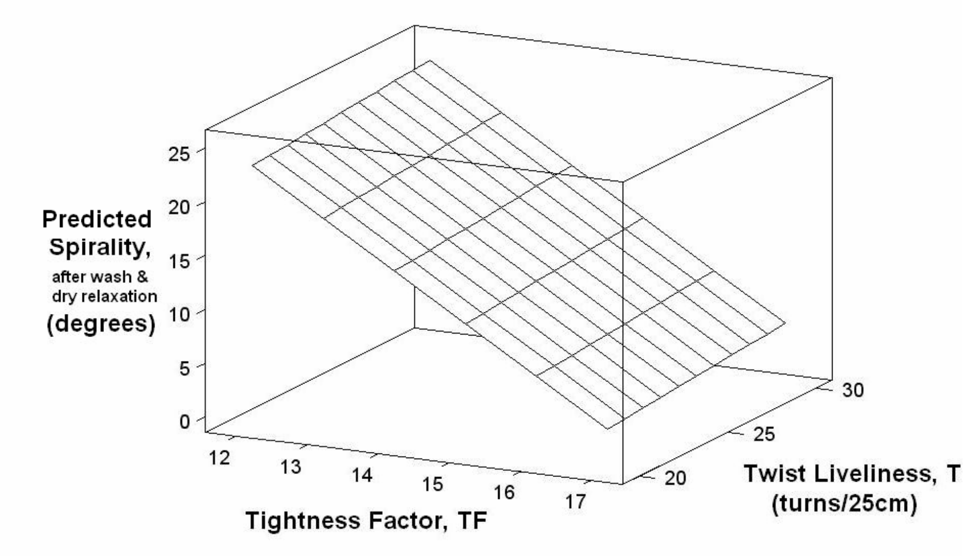



**Figure 5.4 Effect of twist liveliness and tightness factor on spirality**

Furthermore, the model can be applied in practice to estimate or forecast the trend in the change in spirality when considering using yarns with different twist liveliness at different levels of tightness factor within the range used for the model development. Figure 5.5 shows a plot of the predicted average spirality angle as determined by the multiple regression model due to changes in twist liveliness at different levels of tightness factor. Such a figure would allow manufacturers to have an indication of the appropriate yarn and tightness factor to use in order not to exceed their accepted level of spirality. Generally it has been found that a maximum spirality angle of $5^o$ is commercially acceptable (Primentas 1995). It can be seen from the figure that if a manufacturer is considering knitting a Nu-Torque singles ring yarn with similar specification to the Nu-Torque yarn reported in Section 4.4 with an upper limit of the number of snarl turns of 25turns/25cm, a tightness factor above 16.6 $tex^{1/2}$ $cm^{-1}$ would be required.

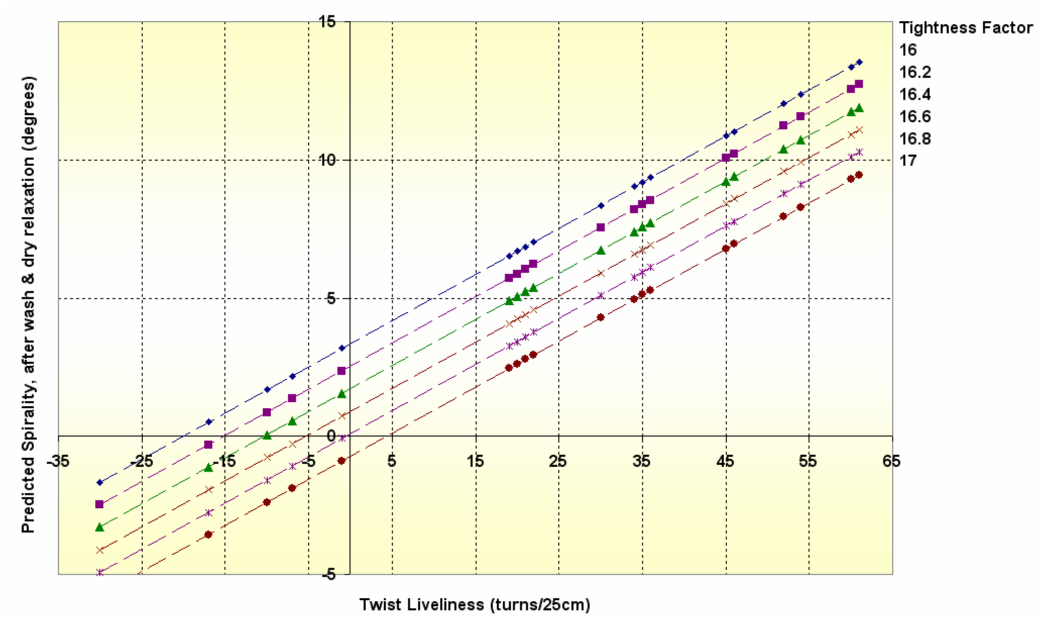



**Figure 5.5 Relationship between spirality and twist liveliness for various values of tightness factors**

## 5.7 THE ARTIFICIAL NEURAL NETWORK MODEL

With suitable training sets, neural networks have been taught to perform well in a wide range of applications. Such as in building predictive models in processes where many factors contribute to the eventual outcome, but where there is little knowledge about the exact relationships or interactions between the input and output parameters (Beltran, Wang & Wang 2004). Thus, the true power and advantage of neural networks lies in their ability to represent both linear and non-linear relationships and in their capacity to learn these relationships directly from the data being modelled.

### 5.7.1 Basic Concept of ANN's

The key element of neural networks is the novel structure of the information processing system. It is composed of a large number of simple processing elements called neurons, also referred to as units, cells or nodes interconnected in some specific architectural way that work together in unison to solve specific problems.

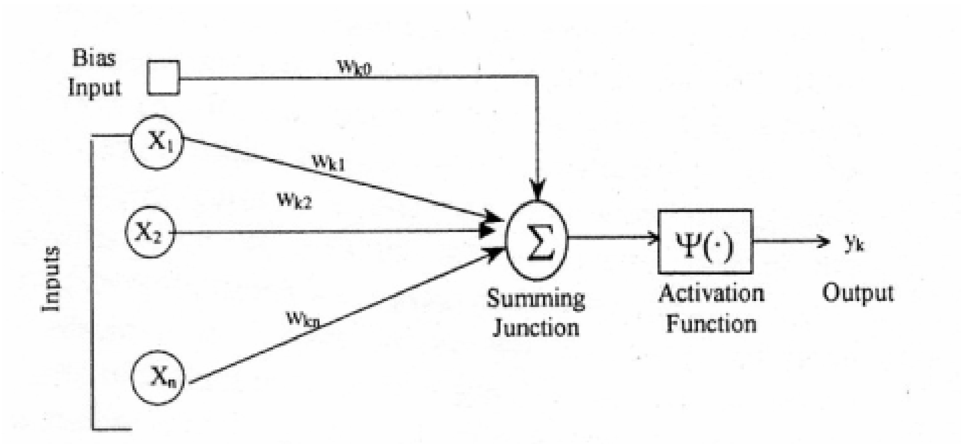



**Figure 5.6 Schematic representation of an artificial neuron**
(Source: Chattopadhyay 2006)

The function of the neuron is to process one or more inputs from another neuron or perhaps from an external source and sum them to give an output. A schematic view of an artificial neuron is shown in Figure 5.6. On the left are the multiple inputs to the neuron ($X_1$, $X_2$….$X_n$). The neuron performs a weighted sum on the inputs which are connected to it with associated connection strengths given as $w_{k1}$, $w_{k2}$…., $w_{kn}$ (Dayhoff 1990). The summing junction receives all the weighted signals and passes it to the output through an activation function. The neuron model also includes an externally applied bias that has the effect of increasing or lowering the net input of the activation function depending on whether it is positive or negative respectively.

In mathematical terms, we may describe a neuron *k* by the following equations:

$$u_k = \sum_{j=1}^{n} w_{kj} x_j \qquad (5.3)$$

$$y_k = \psi(u_k + b_k) \qquad (5.4)$$

Where $x_1, x_2 \ldots, x_n$ are the input signals; $w_{k1}, w_{k2} \ldots, w_{kn}$ are the synaptic weights of the neuron $k$; $u_k$ is the linear combiner output due to the input signals; $b_k$ is the bias; $\psi(\cdot)$ is the activation (or transfer) function; and $y_k$ is the output signal of the neuron (Chattopadhyay 2006).

### 5.7.2 Selection of an Appropriate Neural Network Model

Neural network design is a complex and challenging process, as there are numerous possible architectures available and important decisions are required to establish a suitable and stable network. The first step in designing a neural network is choosing a suitable neural network model based on the nature of the problem. For this study, the task the neural network must perform is prediction and a model appropriate for this type of problem must be selected.

There are a few neural network models that can be used in prediction or mapping problems, including competitive learning networks, adaptive resonance theory networks, probabilistic networks and counter-propagation networks, etc. However, a backpropagation network was selected for the following reasons:

- It is the most powerful learning model in terms of the learning accuracy as many other models can only learn mappings that are linearly separable.
- It does not require prior knowledge of the relationships between input and output variables provided that the training data contains all the important factors that influence the value of the output variables.
- It is flexible in terms of accommodating mixed data types i.e. numeric, ordinal, range.
- The learning algorithm has been well developed, it is easy to use and it has been successfully applied in many prediction problems.

The backpropagation model is a multilayered, feed forward network with supervised learning. It was first described by Paul Werbos in the early 1970s, and was further developed by David Rumelhart, Geoffrey E. Hinton and Ronald J. Williams in the mid 1980s (Dayhoff 1990; Eberhart & Dobbins 1990; Freeman & Skapura 1991; Chester 1993; Fausett 1994). The term backpropagation or back-error propagation refers to the backward propagation of an error signal though the network. Backpropagation belongs to the class of learning or training algorithms that perform gradient descent. That is, it is a descendant of the Widow-Hoff or delta rule (Chester 1993) although there are a number of variations on the basic algorithm.

A typical backpropagation network starts out with a random set of connection weights. During the training stage the input data are repeatedly presented to the neural network. With each presentation, the output of the neural network is compared with the target output and an error signal is generated. This error signal is then propagated backwards to the neural network and used to adjust the connection weights such that the error signal decreases with each iteration process, and the neural network model gets closer to producing the desired output (Majumdar & Majumdar 2004). After extensive training, the network will eventually establish the input-output relationships through the adjusted weights in the network.

To design a backpropagation neural network, the problem must be defined precisely. Data must be collected for training and testing the network. The set of data used for training is important for the success of the network model as the model learns by example. In most applications the data is taken from real data, although sometimes simulated is used as well. However, the training set should use patterns typical of the types of data that the network will encounter later.

In addition, there are a number of aspects that may affect a model's performance and prediction capability. These include:

- Input variables and output parameters.
- Data pre-processing.
- Number of hidden layers and neurons.
- Training method.
- Activation function.
- Stopping criteria.

### 5.7.3 Development of the Neural Network Model

As reported in the previous section, a backpropagation model was selected as the most appropriate model for the prediction of spirality. The model was developed through a procedure as presented in Figure 5.7 and is discussed as follows:

- Data collection – Appropriate data to the problem on hand must be collected with sufficient information for neural network development.
- Data pre-processing – The database should be processed and reorganised to form a new database ready for model development.
- Model design – Various aspects and methodologies have to be selected to suit the type of data and problem involved.
- Model training – Several different neural network structures should be trained and tested and evaluated in order to obtain the structure with the best performance.

- Model performance analysis – Statistical parameters such as the correlation coefficient and resulting errors indicate whether the model is likely to perform well for future data sets.

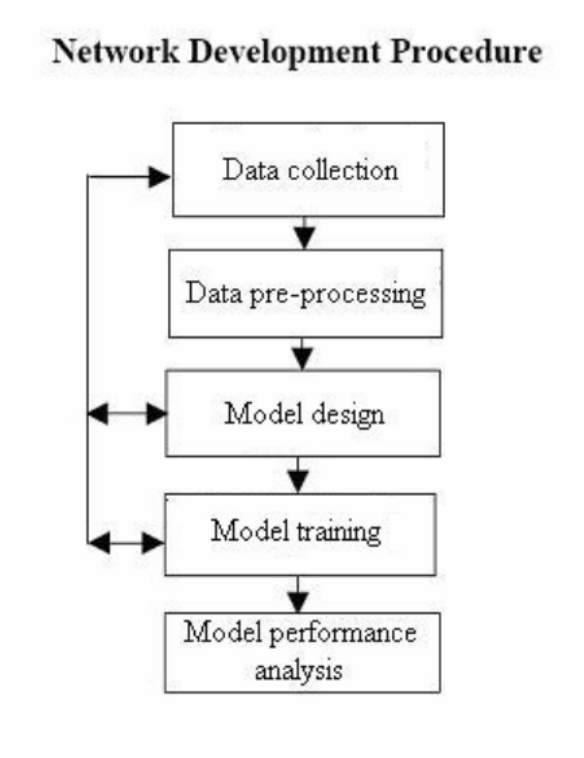



**Figure 5.7 The procedure for neural network development**

To accomplish this work, the Neural Network Toolbox from The Mathworks, Inc (Demuth & Beale 2006) was used. This toolbox runs under The Mathworks' MATLAB program and provides the capability to design many different types of neural network systems for a variety of applications.

### 5.7.3.1 Data collection

In the development of the neural network model, the data obtained from the 60 fabric samples as reported in Section 5.3 were used.

### 5.7.3.2 Data pre-processing

In this work, the data sets were normalised between limits of -1 and +1, with the average value set to zero. The normalised variable $x_{i,norm}$ is represented by:

$$x_{i,norm} = \frac{x_i - x_{i,avg}}{R_{i,\max}} \tag{5.5}$$

and

$$R_{i,\max} = Maximum\left[\left(x_{i,\max} - x_{i,avg}\right),\left(x_{i,avg} - x_{i,\min}\right)\right] \tag{5.6}$$

where $x_i$ is an input or output variable, $x_{i,avg}$ is the average value of the variable over the data set, $x_{i,min}$ is the minimum value of the variable, $x_{i,max}$ is the maximum value of the variable, and $R_{i,max}$ is the maximum range between the average value and either the minimum or the maximum value.

By normalising the data sets in this way it gives some meaning to the values of the normalised variable; 0 represents the normal state of the variable; -1 represents a very low level of the variable, and +1 represents a very high level of the variable. In addition, the network will have a very standard structure that makes training more efficient and consistent from one problem to the next.

**5.7.3.3 Model design**

*Number of hidden layers and neurons*

In this study different network structures were tried with one hidden layer. It has been shown that multilayer feedforward networks with one hidden layer are universal approximators, able to model any complex linear function provided there are a sufficient number of hidden neurons available (Babay et al 2004). The variation between the networks was in the number of neurons in the hidden layer. The number of neurons in the hidden layer varied from 2 to 20 with an increment of two in each step.

For all the networks, there were six inputs as shown in Table 5.1 and a single output which was the degree of fabric spirality after wash and dry relaxation.

*Training method*

The Levenberg-Marquardt algorithm was chosen as the basic learning procedure for the network. According to Demuth and Beale (2006) this algorithm is well suited to problems with networks of moderate size and number of parameters. It is also known to be the fastest method for training moderate sized feedforward neural networks. It operates in batch mode where all inputs are applied to the network before the weights are updated.

It also has a very efficient Matlab implementation because the solution of the matrix equation is a built-in function so its attributes become even more pronounced in a Matlab setting.

The training parameters such as the number of epochs for the Levenberg-Marquardt algorithm were set to the default values in the toolbox.

*Activation function*

The sigmoid function was assigned as the activation function in the hidden layer and the linear function was used in the output layer. The sigmoid function is commonly used in backpropagation networks, in part because it is differentiable.

*Stopping criteria*

Network training would be terminated based on the cross-validation stop criteria to avoid the tendency of the neural network to over-fit the training data. The mean squared error (MSE) was selected as the major criterion to measure the performance of the model because it is very sensitive to even small errors, which is good for comparing small differences of model performances.

The MSE is calculated by:

$$MSE = \frac{\sum_{j=0}^{P}\sum_{i=0}^{N}\left(t_{ij} - y_{ij}\right)}{NP} \qquad (5.7)$$

where $y_{ij}$ is the network output for the data set $i$ at neuron $j$, $t_{ij}$ is the target network output for data sets $i$ at neuron $j$, $P$ indicates the number of output neurons, and $N$ refers to the number of data sets.

**5.7.3.4 Model training**

Generating and training a neural network, and displaying the test results was accomplished using the Matlab's *m-file* scripting capability.

During the training process the data was divided into training, validation and test sets. The training set consisted of 60% of the original data, 20% of the data was set aside as a cross-validation set and the last 20% of the data was used as the test set to evaluate the performance of the network.

Typical training results for the trials of this network are shown in Figure 5.8. The goal of training is to obtain a network with best generalisation capability. Generalisation is defined as the ability of a network to store in its weights general characteristics which are common to a group of examples. A drawback of neural networks is that it is difficult to know at what point the network will over-fit the data which will lead to a loss in generalisation. To try to avoid the likelihood of over-fitting from excessive training, the cross-validation stop criteria was used. As can be seen from Figure 5.8 the validation mean squared error continually falls over 12 epochs beyond which the cross validation error starts to increase. For this particular application, 13 epochs represents the point where sufficient training has occurred prior to over-fitting of the specific solution within the training set.

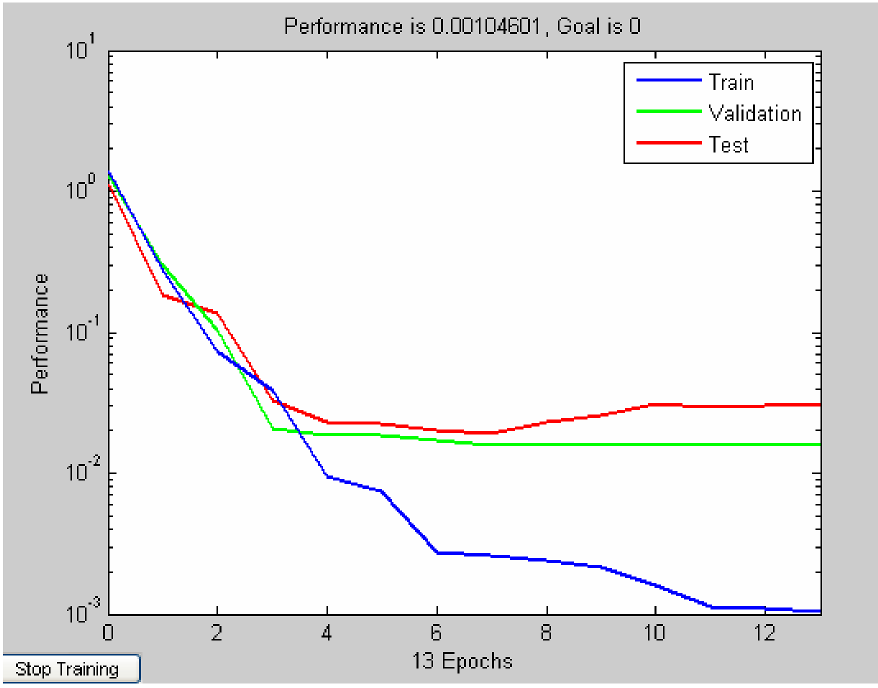



**Figure 5.8 Typical training results for the multilayer network**

*Determination of the optimum number of hidden neurons*

One of the primary aspects of the neural network training process is the selection of the optimal number of hidden neurons. A network with too few hidden neurons would be incapable of differentiating between complex patterns leading to only a linear estimate of the actual trend. Whereas, if a network has too many hidden neurons it will follow the noise in the data leading to poor generalisation for untrained data.

To establish the optimal number of neurons required in the hidden layer, an experimental process was conducted by systematically varying the number of neurons. The effect of the number of hidden neurons from 2 to 20 was studied and the results of the correlation between the actual degree of spirality and the predictions from the models with the different number of neurons are summarised in Table 5.5. Based on these results it can be seen that a network with 18 neurons in the hidden layer gives the best prediction results as it had the highest *R*-value (R = 0.973).

**Table 5.5 Correlation between the actual degree of spirality and the predictions from the models with different number of neurons**

| Number of hidden neurons | Correlation coefficient (R) |
|---|---|
| 2 | 0.96309 |
| 4 | 0.96312 |
| 6 | 0.96263 |
| 8 | 0.93751 |
| 10 | 0.89904 |
| 12 | 0.96130 |
| 14 | 0.95652 |
| 16 | 0.96157 |
| 18 | 0.97337 |
| 20 | 0.95757 |

Consequently, the training results indicate a suitable neural network model for this particular application contains six inputs, one hidden layer with 18 hidden neurons, and an output layer with one output neuron. All the hidden layer neurons have a tansig transfer function, with a single linear neuron in the output layer. The network is fully connected from inputs to the hidden layer to the output layer.

The schematic architecture of the final neural network in this research is presented in Figure 5.9. The computer program of the finalised model is shown in Appendix 5.2.

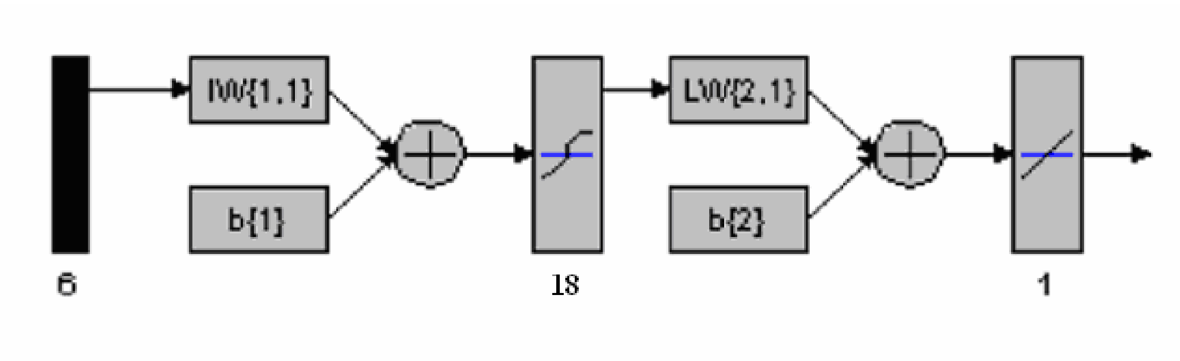



**Figure 5.9 Backpropagation neural network for spirality prediction**

**5.7.3.5 Assessment of the model**

Similar to the results of the multiple regression model in Figure 5.3, the accuracy of the neural network model can be judged by the regression coefficient of the line that relates the fabric spirality predicted by the model and the actual tested values of the spirality of the fabric used for training as shown in Figure 5.10. The figure shows that the prediction is slightly better than the multiple regression model as more points are aligned on the line of perfect fit. In addition, the results show that the predicted values, A, track the measured or actual values, T, very well as the correlation coefficient is high (R=0.973).

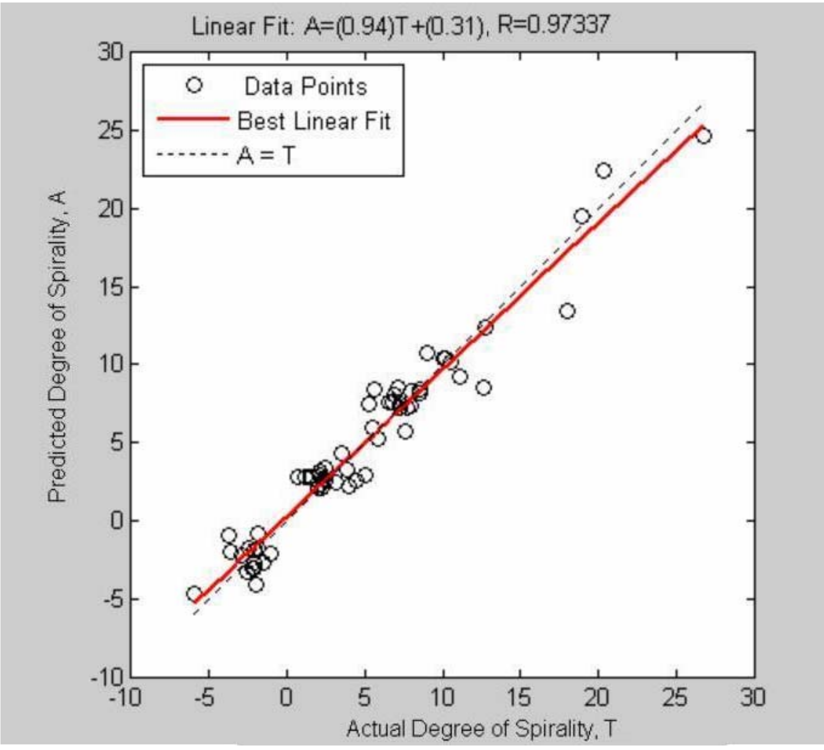



**Figure 5.10 Relationship between the actual and predicted values of spirality for the training set of data (neural network model)**

## 5.8 COMPARISON BETWEEN THE PERFORMANCES OF THE MODELS

After the completion of the model development and training, the multiple regression model and selected neural network model were evaluated with the testing samples that were separated from the main dataset. The testing data is not used in the model development or training in anyway and hence provides an 'out-of-sample' data set to evaluate the models with. This gives some indication of how well the models will perform when presented with data from the real world. The set of data included 12 fabric samples with the parameters shown in Table 5.6.

**Table 5.6 Parameters of the test set**

| Sample No. | **Twist liveliness** (turns/25cm) | **Number of feeders** | **Gauge** | **Rotational direction** | **Piece dyed** | **Tightness Factor** | **Measured angle of spirality (degrees)** |
|---|---|---|---|---|---|---|---|
| **1** | 61 | 1 | 2 | 1 | 0 | 16.37 | 18.06 |
| **2** | 21 | 1 | 2 | 1 | 0 | 16.74 | 2.19 |
| **3** | -7 | 3 | 3 | 0 | 0 | 16.90 | -1.54 |
| **4** | -10 | 3 | 3 | 0 | 0 | 16.83 | -2.27 |
| **5** | -17 | 3 | 3 | 1 | 0 | 17.09 | -2.56 |
| **6** | 21 | 3 | 3 | 0 | 1 | 16.96 | 4.45 |
| **7** | -17 | 3 | 3 | 0 | 1 | 16.96 | -2.15 |
| **8** | 22 | 3 | 3 | 0 | 1 | 16.96 | 2.29 |
| **9** | 22 | 3 | 3 | 1 | 1 | 17.03 | 3.17 |
| **10** | 20 | 3 | 3 | 1 | 0 | 17.03 | 0.70 |
| **11** | 0 | 3 | 3 | 1 | 0 | 17.03 | -1.82 |
| **12** | 20 | 3 | 3 | 1 | 0 | 17.03 | 1.56 |

The testing data were presented to the models and, as a simple comparison of the results, Figure 5.11 shows the spirality values predicted by the multiple regression and neural network models versus the actual 'target' measured values for each of the samples in the test data set. The multiple regression and neural network predictions are reasonably comparable, however it can be seen that for some samples, such as samples one and two, the predicted value from the neural network model is closer to the measured value than the predicted value from the multiple regression model.

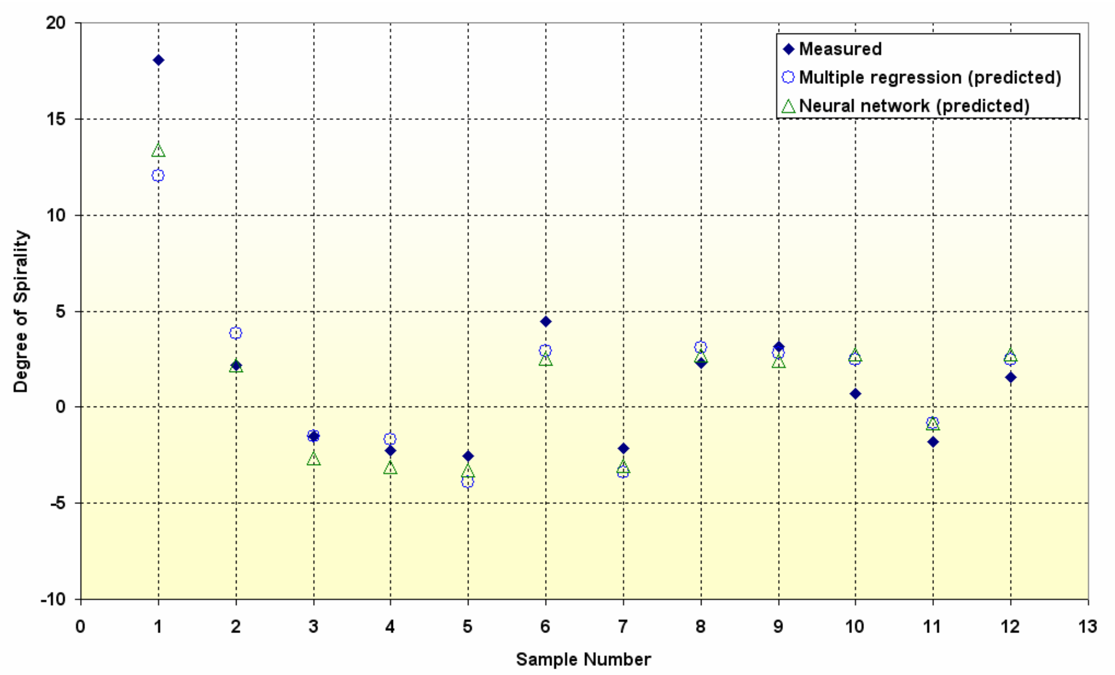



**Figure 5.11 Results of the multiple regression model and neural network model predictions and the actual measured degree of spirality for the test fabrics**

The results were also subjected to further analysis where the predictive accuracy was judged by statistical parameters such as the correlation coefficient between the actual and predicted degree of spirality (*R*), mean squared error and the mean absolute error. The results are shown in Table 5.7.

**Table 5.7 Comparison of prediction performance of the two models**

| Statistical parameter | Regression | Neural Network |
|---|---|---|
| Correlation coefficient, *R* | 0.944 | 0.963 |
| Mean squared error | 4.247 | 3.004 |
| Mean absolute error | 1.440 | 1.302 |

It is evident from Table 5.7 that the predictive power of the neural network model is slightly better than the regression model. The correlation coefficients (*R*) between the actual and predicted degree of spirality are very high for both models but the neural network model has a slightly higher value of 0.963 compared with 0.944 for the regression model. In addition, the mean squared error and mean absolute error for the neural network model are smaller than the resulting errors from the regression model.

According to these results both models give reasonably close predictions of the degree of fabric spirality, so both multiple linear regression and the neural network model can be effectively used for this purpose. On the other hand, it is clear from the results that smaller resulting error values can be obtained by using a neural network model.

## 5.9 CONCLUSIONS

The results from the application of the methodology and apparatus to measure twist liveliness have been used to study the quantitative relationship between yarn twist liveliness and fabric spirality. Additional parameters including tightness factor, number of feeders, machine rotational direction, gauge and piece dyeing were incorporated into the analysis.

The spirality of samples in a dry relaxed state and wash and dry relaxed state was investigated. The results of simple bivariate and partial analyses indicated that twist liveliness is the parameter most significantly correlated with fabric spirality. Tightness factor has a moderately negative correlation, whereas the other parameters have a less important effect on the spirality of both dry relaxed and wash and dry relaxed fabrics.

It was established that spirality could not be predicted with any reasonable degree of accuracy when using fabric samples in their dry relaxed state and the investigation was not carried further for fabrics in this condition. For the wash and dry relaxed fabrics, an empirical equation for the angle of spirality was derived by a stepwise multiple regression technique. The regression analyses revealed the quantitative relationship between the angle of spirality and the twist liveliness and tightness factor. It showed that approximately 63% of the variance in the fabric spirality of the specimens tested is explained by yarn twist liveliness alone. With the inclusion of tightness factor, about 93% of the variance of fabric spirality can be explained.

Until now, Artificial Neural Networks, which are information processing tools inspired by biological neural networks have not been applied for predicting the degree of fabric spirality. This study has shown that such a method of analysis is suitable for the purpose and the neural network model selected was a feedforward backpropagation model. Sixty data sets were used for training and testing different neural network structures using a Levenberg-Marquardt algorithm. According to the investigations, a model with one hidden layer, 18 hidden neurons, a tansig transfer function in the hidden layer and a single linear neuron in the output layer had the best performance.

The derived regressional equation and the neural network model were tested on unseen data and it was found that there was a relatively good agreement between the measured angle of spirality of the fabric samples and both of the models' predicted values. However, the results predicted from the neural network model had smaller resulting errors compared to the regression model.

Although both approaches could help to predict fabric spirality, the statistical approach is well founded. It provides a clear understanding of the influence of the input parameters, twist liveliness and tightness factor, on the degree of spirality after wash and dry relaxation and allows for the exploration of the interrelationships of these factors step by step with a clear understanding of the structures. For instance, the percentage of variance of the factors as an indication of their contribution toward the fabric spirality is known. On the other hand, the artificial neural network approach is a fast predictive tool with self-learning capabilities and with the flexibility to suit further development.

Finally, it can be concluded that the application of the results obtained from the measurement of twist liveliness using the developed methodology and apparatus is effective in the prediction of fabric spirality after wash and dry relaxation processes using either the statistical or the artificial neural network approach.

# CHAPTER 6

# FURTHER DEVELOPMENT OF THE TWIST LIVELINESS MEASUREMENT APPARATUS USING AUTOMATED METHODS

## 6.1 INTRODUCTION

The developed Yarn Snarling Apparatus has been used by several operators throughout various investigations into twist liveliness and in intra-laboratory and inter-laboratory testing.

From this extensive use, it was concluded that the basic design and construction had fully met its objectives in terms of reliability, durability and accuracy and further work on these aspects would not result in any significant improvement. However, it was considered it may be beneficial if improvements could be made to the methodology by shortening the testing time and increasing the efficiency of the procedures. This chapter therefore describes the investigations undertaken in this respect.

In reviewing the methodology used in operating the apparatus as detailed in Chapter 3 it is convenient to break the procedures down into three parts i.e.

- Part 1 - Preparation of yarn samples:

  Ten yarn samples are drawn out from the yarn package one at a time and clamped to the correct length into the apparatus' sample holder. The sample holder containing the 10 samples is placed into the water bath.

- Part 2 - Formation of snarls:

  The samples are allowed to snarl and obtain a state of equilibrium while immersed in the water bath.

- Part 3 - Counting the number of snarl turns:

  The sample holder is taken out of the water bath and laid on the testing bench. The samples are unclamped from the holder one at a time.
  Each sample is placed individually on a twist tester to count the number of snarl turns generated in the sample by the yarn twist liveliness.

In general, Part 1 takes an operator about three to five minutes depending on the operator's skill; Part 2 requires about 3 minutes for the samples to reach a state of equilibrium and Part 3 takes a minimum of about 5 minutes of operator time.

The procedures in Part 1 are carried out manually by an operator but, on review, it is not thought that there are any alternatives that would either improve accuracy or would result in time savings. The existing procedures are efficient, simple, easily learned and reproducible by different operators. The manual actions involved are all mechanical in nature, e.g. drawing off yarn samples; cutting to length; clamping in position etc, and further refinement or attempts at automation would require the addition of mechanical equipment to imitate these actions. This would make the apparatus unnecessarily complicated and may result in the possibility of introducing errors and/or a need for an increase in operator skill. The Part 2 procedure requires no operator input and cannot be accelerated therefore no changes can be proposed.

It is in Part 3 of the methodology that there is scope for using an automated method as an alternative procedure for counting the number of snarl turns. The concept is to use digital image processing to replace the manual actions of handling the yarn samples during the snarl turn counting procedure. In addition to increasing efficiency, this would also have the advantage of avoiding the need for manually handling wet yarn samples when taking them out of the water bath and counting snarls while in the proximity of delicate equipment on the laboratory bench. Also, without the need for twist testers in the snarl counting process, it reduces the possibility of additional system errors.

## 6.2 OVERVIEW OF THE AUTOMATED METHOD TO COUNT THE SNARL TURNS

The process with potential for automation is concerned with the snarl turn determination. To reduce the testing time and the amount of manual operation involved in counting the number of snarls, a solution would be to replace the method of using a twist tester by an automated visual assessment technique. Recent advances in imaging technology have produced inexpensive, high quality image acquisition and enhanced computer technology that allow image processing and analysis to be performed quickly and inexpensively (Jeong, Choi, Kim, Jaung & Kim 2001). As a result, several image based techniques have been developed for use in textile manufacturing and in testing product quality control. Some examples of applications of image based techniques that have been developed recently include pilling evaluation (Behera & Madan Mohan 2005); drape analysis (Robson, & Long 2000; Behera & Pangadiya 2003); fabric bagging evaluation (Yeung, Li, Zhang & Yao 2002); water repellency evaluation (Nada & Okamura 2002).

In a typical image based system, images of the features of interest are acquired, processed and analysed. Image processing is the application of mathematical function(s) to simplify and/or enhance the captured image data whereas image analysis is the extraction of key numerical data from the final processed image (Robson, & Long 2000). The features of the prepared yarn test samples lend themselves particularly well to this technique as the snarl turns can be distinguished from the appearance of the snarled samples. Figure 6.1 shows samples under test in the water bath and the close-up image of part of a snarled sample illustrates the snarl turn feature that could be analysed to produce a count of the number of snarl turns generated in the samples.

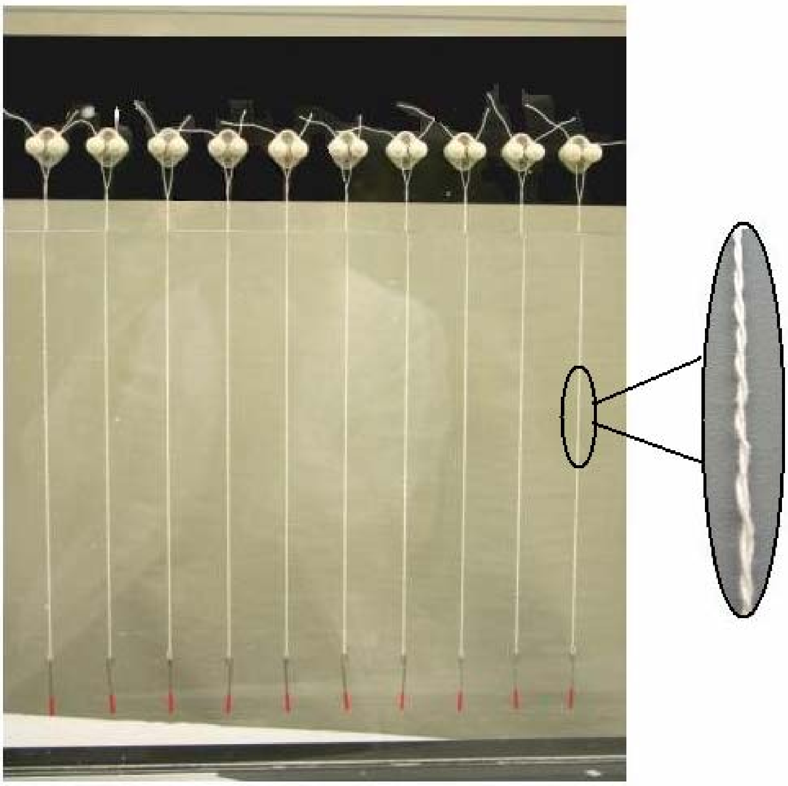


**Figure 6.1 Image of the samples under test in the water bath**

## 6.3 DEVELOPMENT OF THE AUTOMATED METHOD

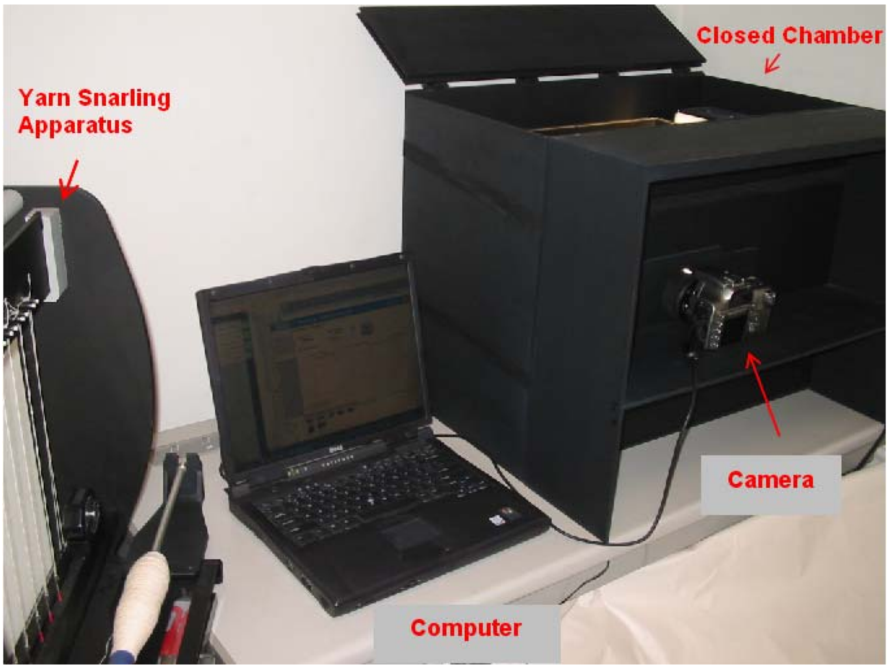
The fundamental aim of this work is to characterise the yarn snarling of the test specimens by using a digital image based system. Digital image processing and analysis is not a one-step process; there must be a series of several steps that should be performed until the data of interest can be extracted from the image (Jahne 2005, p.15). The basic assumption of any image based method is that the captured image perfectly represents the object. The assumption is not exactly correct due to various incidental problems associated with image capturing such as noise and resolution problems etc. Although these difficulties can be minimised by careful selection of settings, the best way to overcome the problems is to standardise the method. Keeping this in mind the various settings were kept constant and the following are the general steps that were used to determine the number of yarn snarls:

- Image acquisition
- Image conversion
- Image analysis

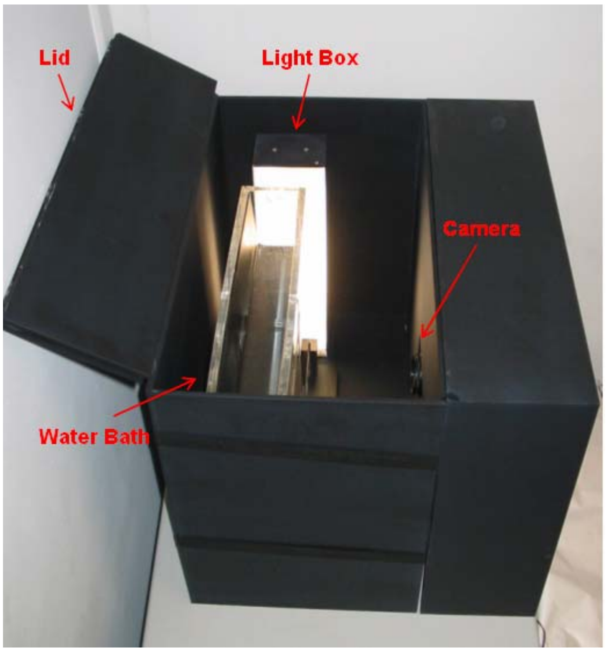
To accomplish this work, the Image and Signal Processing Toolboxes from The Mathworks, Inc was used. These toolboxes run under The Mathworks' MATLAB program and provide the capability of running a range of image manipulation techniques (processing and analysis) that could be operated as part of a multistage routine.

### 6.3.1 Image Acquisition

The image acquisition set-up is important in capturing a suitable image for further processing. The aim of the procedure is to acquire the image of the snarled yarn samples while they are submerged in the water bath which formed part of the original apparatus as shown in Figure 3.2. The water bath is made of transparent acrylic sheet and the samples can be seen however, as they are underwater, there are restrictions on visibility and light reflections from the surface of the acrylic may occur. Therefore the image environment was standardised by using a closed chamber with a controlled illumination system to exclude the effect of other light sources on the images. The chamber has a camera platform and camera computer interfacing arrangement so as to acquire the image and to transfer it to a computer for processing. The image acquisition set-up is shown in Figure 6.2(a) and (b).




**(a) The image acquisition unit set-up**




**(b) An inside view of the closed chamber**

**Figure 6.2 Image acquisition unit**

As can be seen from Figure 6.2(b) the water bath was positioned inside the chamber during testing. Once the samples have been prepared by the methodology reported in Section 3.5 they were placed into the water bath and allowed to reach equilibrium (approximately three minutes). As soon as the samples had reached equilibrium, i.e. no rotational movement, an image of the snarled samples in the water bath was captured. In order to capture the correct test length, marks were placed at two points corresponding to the top and bottom of the samples. This was to ensure that the points were included in the image when fixing the position of the image capturing device and were defined as the point at the bottom edge of the sample holder to the point at the top of the dead weight. A matte black background was used to provide contrast against the yarn samples to allow for easy segmentation of the snarl turn images.

Two main considerations were identified to achieve consistent image capture: image resolution and lighting.

#### 6.3.1.1 Image resolution

Obtaining an optimum image resolution is important in accurately assessing the number of snarls. Low resolution images will create difficulties in differentiating samples, while high resolutions will increase processing time and file sizes. In this application, the main challenge was to achieve an appropriate resolution for the yarn samples which are very long and thin. An acceptable resolution was achieved using a Canon EOS 300D camera at 6.3 mega pixels. The image sensor in this camera is a

CMOS (complementary metal oxide semiconductor) which contains a grid of photosites that convert light shining on them into electrical charges. These charges can then be measured and converted into digital numbers that indicate how much light hits each site; the brighter the light, the higher the charge. When the camera shutter closes and the exposure is complete, the sensor "remembers" the pattern it recorded. The various levels of charge are then converted to digital numbers that can be used to recreate an image that can be processed by a computer.

An important aspect is to set the camera to maintain a correct depth of field (DOF), which is the range of distance around the focal plane within which images are acceptably sharp. An out of focus image would make it hard to clearly threshold the samples' edges so that they can be clearly separated from the background and this may lead to an inaccurate analysis.

**6.3.1.2 Lighting**

One of the most important aspects to optimise the samples' edge contrast and snarl detail is the proper choice and positioning of a light source appropriate to the system's working environment.

A good, well positioned light source will allow the image processing system to receive the best image under the circumstances with the main aim being to establish a homogeneous and constant illumination over the area of interest. Several types of light source are available, however in this application a compact fluorescent light was used as it has a large homogeneous illumination field and does not get very hot. Due to these advantages this type is often used to illuminate scenes for image processing.

Depending on the position of the camera and the light source there are different ways to light the scene. Hence, several lighting set-ups were examined and it was found that diffuse lighting was required as the surface of the water bath reflected strongly if direct lighting was applied. To achieve the diffuse lighting, a light box with an opaque cover was produced. Dark-field illumination was used which highlights the light object against a dark background and it was achieved by placing the light box to the left side of the water bath.

### 6.3.2 Image Conversion

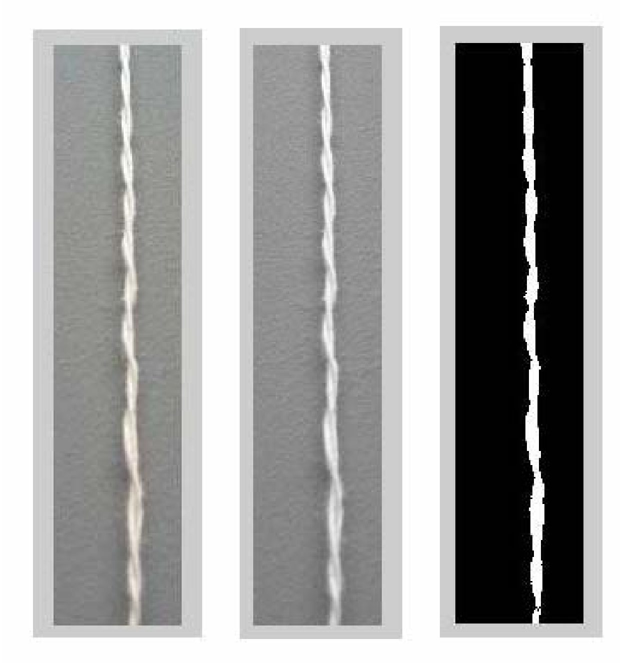
Once the raw image was captured the image of the yarn samples had to be converted into an image that is suitable for conducting measurements. In order to characterize the yarn snarls, features in the image must be well identified and details not of interest must be removed.

An image is represented as a matrix with M rows and N columns as show in Equation (6.1). Each spatial index contains individual pixel colour data. These pixels contain three values reflecting the red, green and blue colour components of the image. This format lends itself to systematic processing and data access.

$$f(x, y) \quad \begin{matrix} f(1, 1) & f(1, 2) & \dots & f(1, N) \\ f(2, 1) & f(2, 2) & \dots & f(2, N) \\ : & : & & : \\ f(M, 1) & f(M, 2) & \dots & f(M, N) \end{matrix} \qquad (6.1)$$

By converting the image to a greyscale, and then a binary image, the desired information can be represented in a condensed form for easy manipulation.

There are several steps required to successfully transform the captured colour image into binary form that can be used in processing. The colour image is transformed to greyscale by taking the weighted sum of the red, green and blue components to produce an 8-bit image with 256 shades of grey. This image is then automatically thresholded according to a global thresholding algorithm to produce a binary image. In this process, pixels with a grey level above the threshold are set to 1, whilst the rest are set to 0 and are interpreted as white and black respectively. The image processing progression is shown in Figure 6.3.



(a) (b) (c)

**Figure 6.3 Conversion of the captured colour image (a) original image (b) greyscale image (c) binary image**

Once a binary image has been derived, subsequent operations can be used to further analyse the image towards extracting the number of yarn snarling turns.

### 6.3.3 Image Analysis

#### 6.3.3.1 Yarn density profile

The image analysis mainly involves two stages of snarl feature extraction and pattern recognition. The working principle of the snarl feature extraction is schematically illustrated in Figures 6.4 to 6.6. Figure 6.4 shows a numerically simulated 3D yarn structure with a uniform distribution of snarls. Supposing the 3D yarn is placed in the water bath, a 2D projection of the yarn can be obtained in Figure 6.5(a), which can also be considered as a simulation of the yarn image captured by the camera.

A close look at the simulated yarn sample in Figure 6.5(a) shows the periodic appearance of the yarn snarls and most importantly its top and bottom boundaries that appear to be two oscillating curves with a fixed frequency. The two oscillating curves can be numerically calculated and highlighted in Figure 6.5(b). By comparing Figures 6.5(a) and 6.5(b), it can be recognised that the number of yarn snarls can be represented by the number of peaks along either of the oscillating curves.

Therefore, a very important characteristic curve for the identification of yarn snarls, called a yarn density profile, can be defined as the yarn cross-sectional width along its length. The yarn density profile for Figure 6.5(b) can be obtained by calculating the vertical difference of each pair of points with the same horizontal location on the two oscillating curves. The calculated yarn density is shown in Figure 6.6. It can be seen that the yarn density profile in Figure 6.6 also presents an oscillating feature with the same frequency as that of the oscillating curves shown in Figure 6.5(b). In addition, compared with the two boundary oscillating cures in Figure 6.5(b), the yarn density profile possesses a magnified oscillation effect which will greatly benefit the accuracy of the following pattern recognition algorithm.

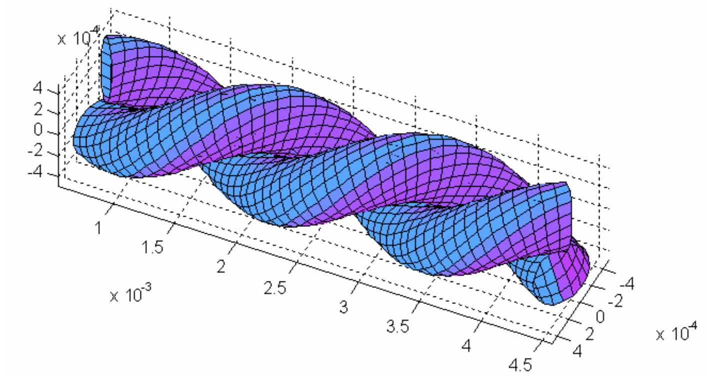
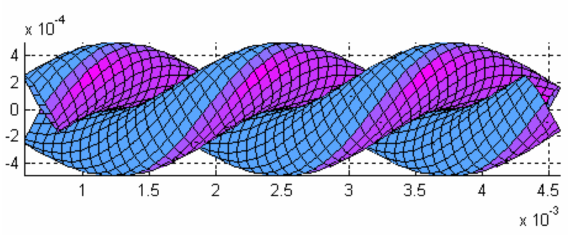
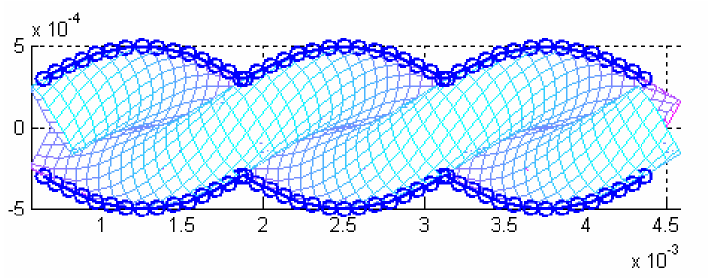



**Figure 6.4 Simulated 3D yarn structure with a uniform distribution of snarls**




**(a) 2D projection**




**(b) Oscillating curves**

**Figure 6.5 Simulated 2D yarn structure with a uniform distribution of snarls**

To calculate the number of yarn snarls in Figure 6.4, only the number of peaks contained in the yarn density profile need to be determined. In Figure 6.6, it can be seen that there are three peak values on the yarn density profile, thus the number of yarn snarls in Figure 6.4 is 3/2=1.5 turns. The process seems quite simple and straightforward by just locating the local maximal values, but usually the real yarn density profile obtained from the yarn image presents a very complex appearance because of the variety of errors. Figure 6.7(b) shows such an example of the yarn density profile obtained from a binary yarn image in Figure 6.7(a). It can be seen from Figure 6.7(b) that the complexities of the real yarn density profile include: (1) the high-frequency noises and many “fake” local maximal values; (2) variable oscillating frequency and magnitude; and (3) some local pulses. Consequently the algorithm for locating the local maximal values for the identification of yarn snarls will fail because there exist many “fake” maximal values which are mainly produced by the noise rather than the oscillations contained in the yarn density profile. Therefore the next challenge is to propose a robust algorithm for the accurate identification of the number of peaks or oscillations contained in a complex yarn density profile. This constitutes the next processing stage of pattern recognition.

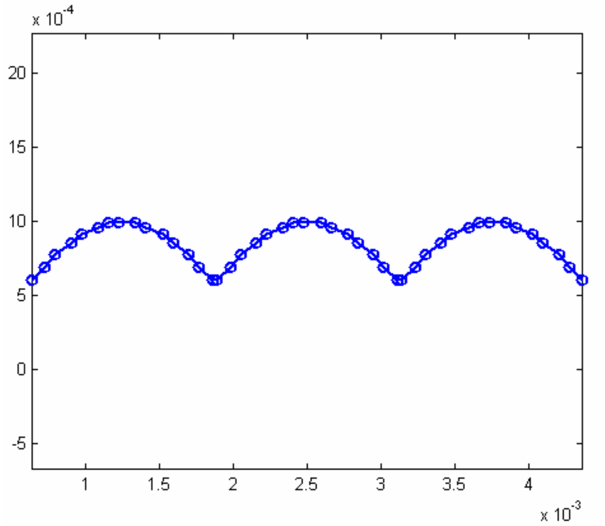
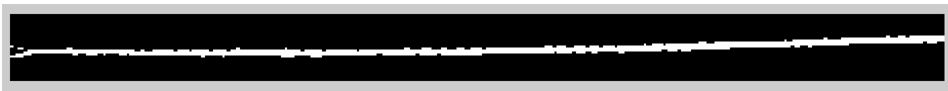
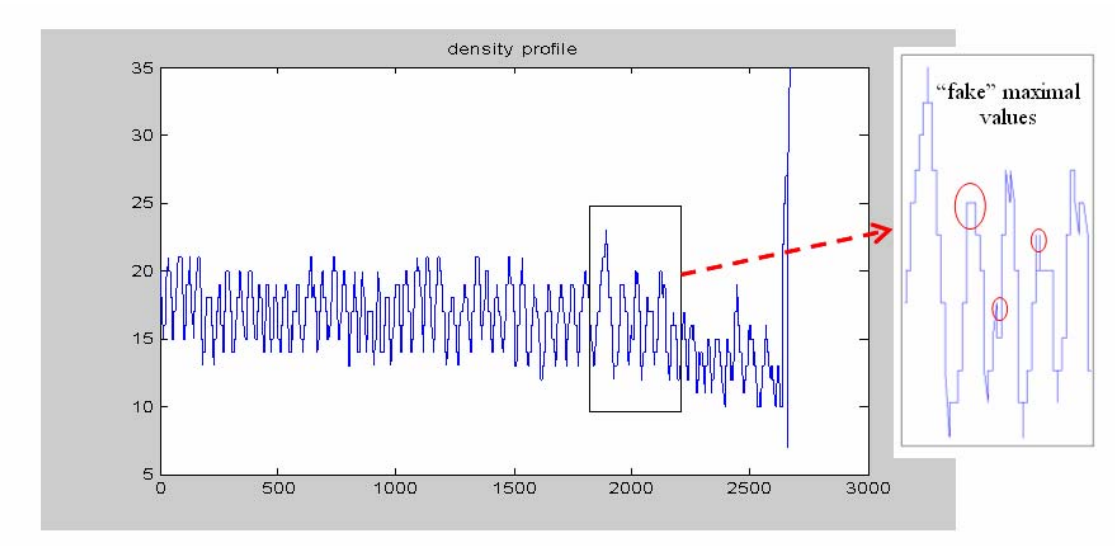



**Figure 6.6 Yarn density profile of the simulated yarn sample**



**(a) Binary image of an actual yarn sample**




**(b) Density profile of the actual yarn sample and illustration of the "fake" maximal values**

**Figure 6.7 An actual yarn sample**

### 6.3.3.2 Pattern Recognition Algorithm

The pattern recognition for the identification of peaks or oscillations contained in the yarn density profile consists of two algorithms, namely Fast Fourier Transform (FFT) and Adaptive Orientated Orthogonal Projective Decomposition (AOP). Firstly in the FFT algorithm, the yarn density profile is treated as a one-dimensional digital signal and the fluctuation frequency of the yarn density profile caused by yarn snarling can be approximately estimated by calculating the corresponding basic frequency component. Then the basic frequency will be used as an important input to the following AOP algorithm, wherein all fluctuations in the yarn density profile can be accurately simulated by the Gauss-functions of different character parameters. The number of Gauss-functions used for the simulation will indicate the half number of the yarn snarls.

*Fast Fourier Transform (FFT)*

A Fast Fourier Transform (FFT) is an efficient algorithm to compute the discrete Fourier transform (DFT) and it's inverse. FFTs are of great importance to a wide variety of applications, from digital signal processing and solving partial differential equations to algorithms for quickly multiplying large integers (Russ 2002).

The Fast Fourier Transform (FFT) is commonly used in numerical analysis to transform a digital signal between spatial and frequency domains. The FFT decomposes a digital signal into sines and cosines of varying amplitudes and phases.

The values of the resulting transform represent the amplitudes of particular frequencies. Usually this signal information in the frequency domain can be used to show how often certain patterns are repeated within a signal.

The following Figure 6.8 shows the results of applying the FFT to the yarn density profile in Figure 6.7(b). It can be seen that the yarn density profile consists of a full range of non-zero frequencies in the frequency domains which verifies the complexity of the yarn density as discussed in the previous section. The high frequencies (above 10Hz) correspond to abrupt variations or high-frequency noises, while the low frequencies may contain some useful information. A close look at the low frequency band indicates that the yarn density profile is composed of many oscillations with different frequency and magnitude. Although there are many components of low frequency, a basic component of the highest magnitude can be found in Figure 6.8 which approximately stands for the frequency in terms of periodic elements of the yarn density profile. As the basic component is a fixed component, it cannot precisely describe the oscillations with different frequencies and magnitude in Figure 6.7(b). Nevertheless by calculating this basic frequency it can provide an estimate of the fluctuation frequency of the yarn density profile to the following AOP algorithm and is used to calculate the initial variance of the Gaussian function in Equation 6.7 below.

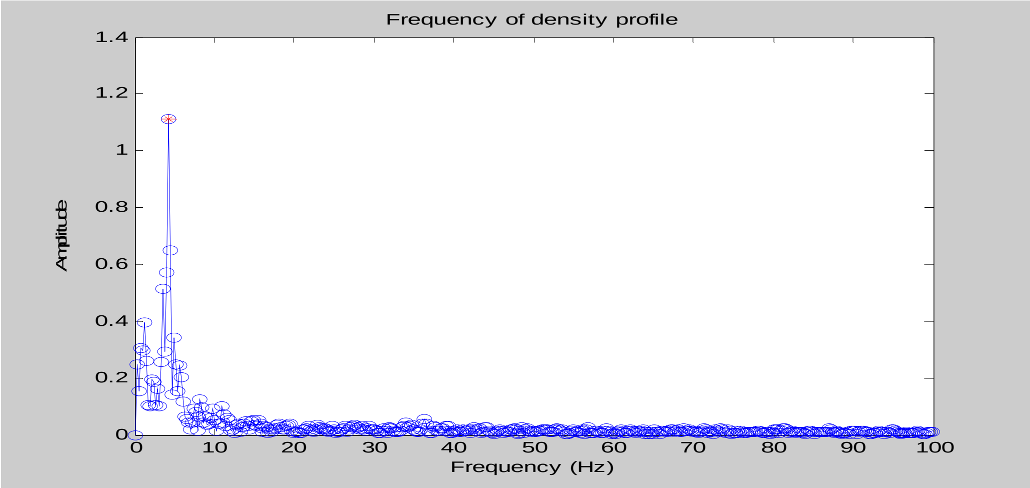



**Figure 6.8 Result of applying FFT to the density profile of the actual yarn sample**

*Adaptive Orientated orthogonal Projective Decomposition (AOP)*

Adaptive signal decomposition is an essential tool for signal modelling and processing. Various approaches have been proposed since the 1990s. A general adaptive signal decomposition is described as follows (Yin, Qian & Feng 2002).

For a given signal $s(t)$ and a set of pre-defined atom signals $G = \{g(t)\}$, first select an atom signal $g_0(t)$ from $G$ so that the distance between $s(t)$ and its orthogonal projection on $g_0(t)$ is minimised:

$$\min_g \|\boldsymbol{s}_1(t)\|^2 = \min_g \|\boldsymbol{s}_0(t) - \langle \boldsymbol{s}_0(t), \boldsymbol{g}_0(t)\rangle \boldsymbol{g}_0(t)\|^2 \tag{6.2}$$

Here $\langle\ ,\ \rangle$ denotes the inner product of the signal vector where $\boldsymbol{s}_0(t) = \boldsymbol{s}(t)$.

$\boldsymbol{s}_1(t)$ is the residual signal after subtracting the projection of $\boldsymbol{g}_0(t)$ from the original signal $\boldsymbol{s}(t)$, and

$$\begin{aligned}\boldsymbol{s}_1(t) &= \boldsymbol{s}_0(t) - \langle \boldsymbol{s}_0(t), \boldsymbol{g}_0(t)\rangle \boldsymbol{g}_0(t) \\ &= \boldsymbol{s}_0(t) - A_0 \boldsymbol{g}_0(t)\end{aligned} \tag{6.3}$$

where $A_0 = \langle \boldsymbol{s}_0(t), \boldsymbol{g}_0(t)\rangle$.

Repeating this process, we can have

$$\begin{aligned}\boldsymbol{s}_{k+1}(t) &= \boldsymbol{s}_k(t) - \langle \boldsymbol{s}_k(t), \boldsymbol{g}_k(t)\rangle \boldsymbol{g}_k(t) \\ &= \boldsymbol{s}_k(t) - A_k \boldsymbol{g}_k(t)\end{aligned} \tag{6.4}$$

Therefore, the original signal $\boldsymbol{s}(t)$ is decomposed by $K$ atom signals:

$$\boldsymbol{s}(t) = \sum_{k=0}^{K} A_k \boldsymbol{g}_k(t) + \boldsymbol{s}_{k+1}(t) \tag{6.5}$$

The choice of atom signals $G$ depends on the nature of the applications. For example, a chirplet or a Gaussian chirplet is usually adopted as an atom signal (Bultan 1999) in the field of voice signal processing, since it is able to characterise the time-frequency properties of voice signals. In this case, an atom signal is required which can describe the morphological property of a yarn snarl. A normalized Gaussian function is employed as the atom signal which can be written as:

$$g_l(z) = (\pi\sigma_l)^{-0.25} e^{-\frac{(z-\mu_l)^2}{2\sigma_l^2}}, l = 1,2,...\infty . \tag{6.6}$$

It was chosen as the atom signal because the shape of a normalised Gaussian function can approximate the shape of the oscillations of the yarn density profile and thus can represent the morphological property of a yarn snarl. Furthermore, unlike other methods for characterising time-varying signals such as Gabor expansion and wavelet decomposition, the time and frequency resolution and time-frequency centres of the normalised Gaussian elementary functions are adjusted to best match the signal under consideration. Numerical simulations have also indicated that is it economical in representation and produces reliable results in the presence of random noise (Qian & Chen 1994).

By using adaptive signal decomposition, the yarn density profile signal can be decomposed into a number of Gaussian functions. Each Gaussian function corresponds to half of a yarn snarl, so the number of yarn snarls can be determined by counting the number of Gaussian functions used.

An important issue in the application of adaptive signal decomposition for yarn snarl detection is the computing complexity. Yin, Qian and Feng (2002) proposed an efficient algorithm, named adaptive orthogonal projection decomposition (AOP) algorithm, for parameter estimation of the atom signals. Nevertheless, there are two key issues that have to be settled before employing the AOP for the yarn snarl detection, i.e. determination of the initial variance of Gaussian function and the termination condition of the AOP algorithm. For this case, the estimate of yarn oscillating frequency calculated by the FFT algorithm discussed in the previous section can be used to calculate the initial variance of Gaussian function:

$$\sigma = \frac{1}{6f} \tag{6.7}$$

where $f$ is the basic frequency calculated by the FFT algorithm discussed in the previous section and $\sigma$ is the initial variance of the Gaussian function.

For the termination condition, the AOP algorithm will terminate as long as the magnitude of the Gaussian function to be used is less than one-third of the average magnitude of the Gaussian function. Therefore the number of the Gaussian functions employed in an AOP algorithm represents the half number of the yarn snarls.

Figure 6.9 is the decomposition results of the yarn density profile in Figure 6.7 (b) in terms of Gaussian functions. It can be seen that there are a total of 59 Gaussian functions used for the decomposition, therefore the number of yarn snarls in Figure 6.7(a) is 59/2=29.5 turns. A close look at the figure shows that the Gaussian function can match the oscillations of the yarn density profile adaptively and accurately, and the algorithm is robust to the noises and the variable oscillating frequency and peak magnitude in the yarn density profile.

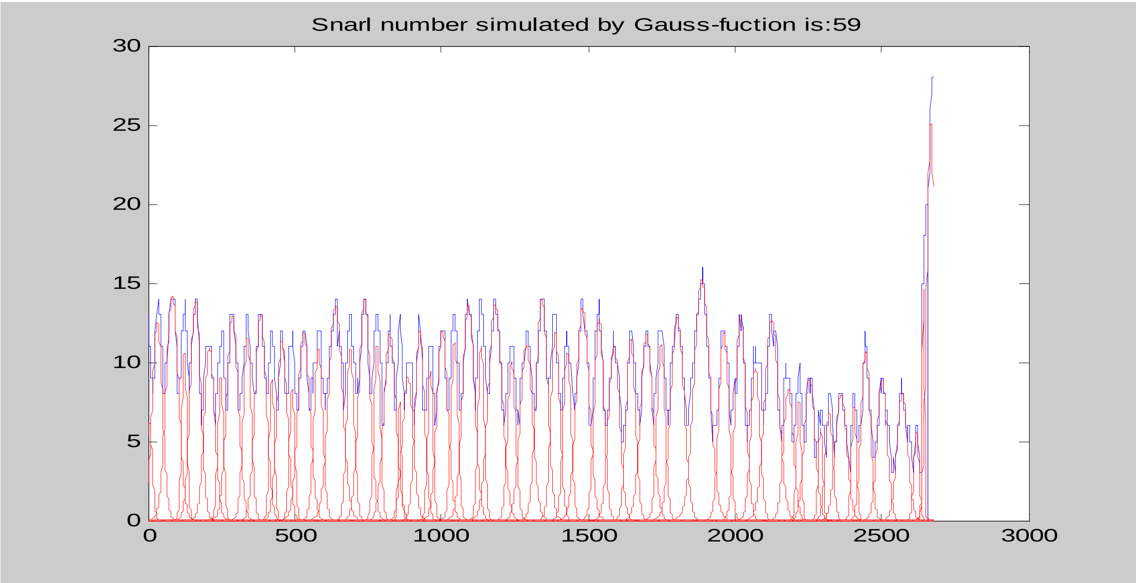



**Figure 6.9 Decomposition results of the actual yarn sample**

## 6.4 TESTING OF THE AUTOMATED METHOD

The methodology to measure twist liveliness requires the counting of the number of snarl turns. To investigate the use of the automated method using image processing to undertake this task it is necessary to test its equivalence with the previously established manual method.

### 6.4.1 Experimental

In order to test the automated system, four 100% cotton greige Nu-Torque singles ring yarn specimens were collected. It was considered appropriate to use these low twist lively yarns because one of the main uses originally proposed for the apparatus was to test the performance of methods to produce low torque yarns and to ensure that the quality of the yarns is consistent during production.

The details of the specimens are shown in Table 6.1 This set was chosen to examine the accuracy of the automated method over a variety of yarn counts.

**Table 6.1 Specimen details**

| Specimen Number | Yarn count | | Nominal twist level (tpm) |
|---|---|---|---|
| | Ne | Tex | |
| 1 | 7 | 83.36 | 333 |
| 2 | 10 | 59.05 | 398 |
| 3 | 16 | 36.91 | 384 |
| 4 | 20 | 29.53 | 440 |

All the specimens were conditioned under a relative humidity of 65% ± 2% and a temperature of 20 ± 2$^{o}$C. For each specimen 50 samples were prepared and clamped into position on the sample holders of the Yarn Snarling Apparatus following the methodology in Section 3.5. The sample holders were placed into the water bath which was positioned in the image acquisition unit.

The standard testing procedure and apparatus allows for 10 samples to be positioned in the sample holder at a time. However it was found through several trials, using one camera as shown in Figure 6.2, that a maximum of five samples could be captured in one image while still obtaining acceptable results in terms of image quality for further processing.

The testing procedure was therefore conducted using 5 samples at a time. As soon as the samples had reached their snarled equilibrium state in the water an image was captured and sent to the computer for analysis.

The sample holder containing the same 5 samples was then removed from the water bath in the image acquisition unit and the standard manual procedure using a twist tester was employed to measure the twist liveliness of each sample by counting the number of snarl turns. The output from the computer program in terms of the number of snarl turns for each of the 50 samples of the 4 specimen yarns and the results of the manual method of counting snarl turns for the same samples were then tabulated and analysed.

### 6.4.2 Results and analysis

The ability of the automated method to reduce the testing time was assessed by timing the process to obtain the results for each method. On average it was found that the automated method took approximately one to two minutes to capture and process the image to obtain the results from one batch of 5 samples held in the sample holder. In comparison, it was established that a skilled operator took 4 to 5 minutes to obtain the results from the same 5 samples using the manual method.

The results of the mean and standard deviation values of the twist liveliness (number of turns/25cm) of the same 50 samples tested from each of the four yarn specimens using the automated and manual methods are summarised in Table 6.2. As expected, it can be observed that each specimen had different levels of twist liveliness. The lowest mean value was 20 turns/25cm for Specimen 1 and the highest mean value was 25 turns/25cm for Specimen 2. The difference between the mean values of the automated and manual method for each specimen was not very large as the specimen with the largest difference was Specimen 3 with a difference of 2 turns. However, in comparing the automated method with the manual method, it can be seen that generally the automated method produced a larger variation in the results. For example the standard deviation of the measurements for Specimen 4 using the automated method was 3.29 compared with 1.94 using the manual method.

To analyse this further, frequency distributions of the differences in the number of snarl turns counted when using the automated and the manual methods for the same 50 samples are illustrated in the histograms in Figures 6.10(a) to (d). As shown in the Figures, the highest number of samples with no difference between the results obtained using the automated and the manual method was 12 for Specimen 1. Specimen 1 also had the smallest range of differences in the number of turns counted for a sample as the maximum difference was ±4 turns compared to a difference of ±8 turns for samples from Specimen 4.

As a statistical analysis, a paired *t*-test was performed to determine whether there was any significant difference between the results obtained by the automated and the manual methods. Differences with $p<0.05$ would be considered to be statistically significant.

Typically, the following hypotheses are set up in the *t*-test:

$H_0: \mu_d = \mu_0$

$H_1: \mu_d \neq \mu_0$

Where, $H_0$ and $H_1$ are the null and alternate hypotheses; $\mu_d$ is the population mean of the differences and $\mu_0$ is the hypothesized mean of the differences.

The null hypothesis is defined so that the hypothesis will be rejected if the means of two sets of results are not equal to each other. Table 6.3 shows that the mean difference between the automated and manual methods is not significant for the Specimen 1 (p=0.057) and Specimen 4 (p=0.588) samples. Therefore, we fail to reject the null hypothesis, as there is insufficient evidence to suggest any difference in measuring the number of turns, on average, using the two methods for these samples.

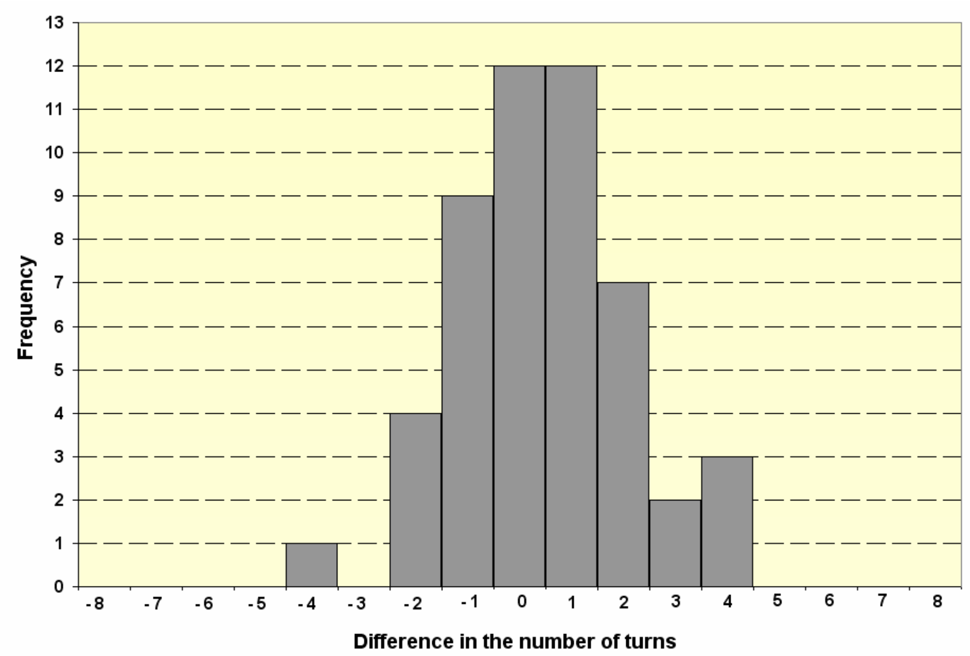
However there is evidence that there is a difference between the results obtained from the automated and manual methods for Specimens 2 and 3 ($p<0.05$) where the mean differences are just over one snarl turn. Although this is statistically significant it is a relatively small difference in practical terms. Thus, it is useful to examine the 95% confidence interval for the mean differences to determine within what limits the true difference is likely to lie. The 95% confidence interval results in Table 6.3 show that the true mean difference for the Specimens 2 and 3 are -1.1 ± 0.7 turns and -1.5 ± 0.6 turns respectively. This confirms that, although the difference in the number of turns is statistically significant, it is actually relatively minor.

**Table 6.2 Mean and standard deviation for twist liveliness of the yarn samples using the automated and manual methods**

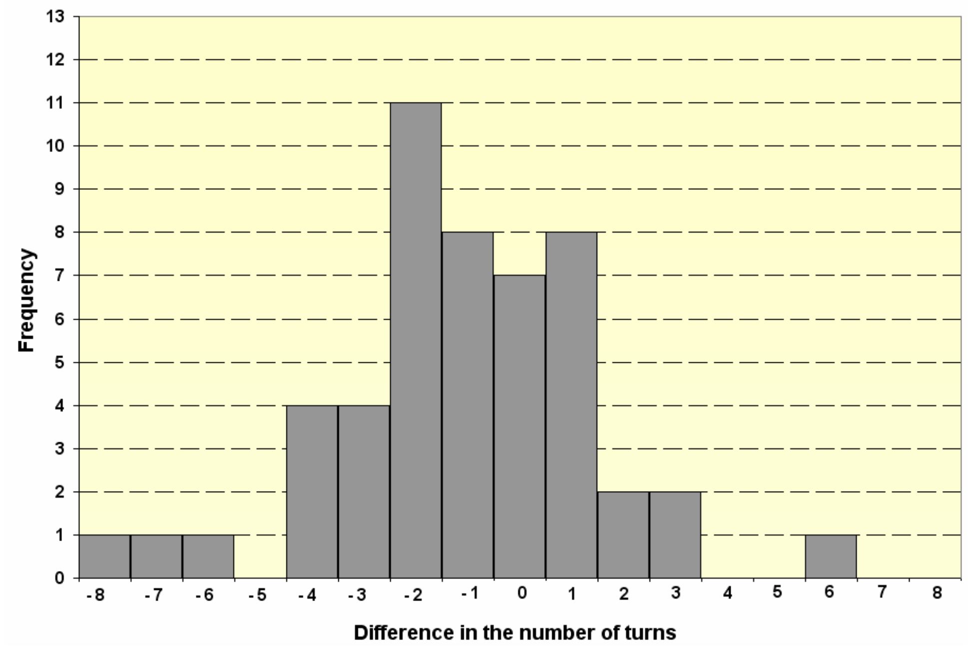
| Specimen | Twist liveliness, number of turns/25cm | | | |
|---|---|---|---|---|
| | Automated | | Manual | |
| | Mean | Std. | Mean | Std. |
| 1 | 20 | 2.00 | 20 | 1.64 |
| 2 | 24 | 2.53 | 25 | 1.51 |
| 3 | 21 | 2.26 | 23 | 2.03 |
| 4 | 24 | 3.29 | 24 | 1.94 |

**Table 6.3 Results of the paired t-test**

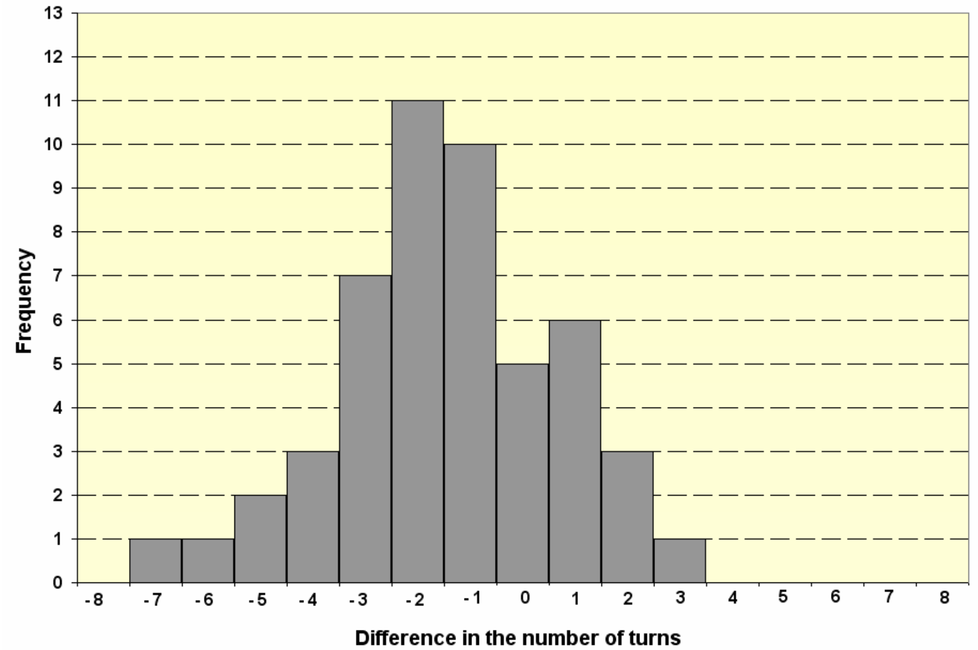
| Specimen | t-value | df | p-value | Mean Difference | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| 1 | 1.95 | 49 | 0.057 | 0.5 | -0.01 | 0.93 |
| 2 | -3.09 | 49 | 0.003 | -1.1 | -1.82 | -0.39 |
| 3 | -4.87 | 49 | 0.000 | -1.5 | -2.06 | -0.86 |
| 4 | 0.54 | 49 | 0.588 | 0.2 | -0.65 | 1.13 |



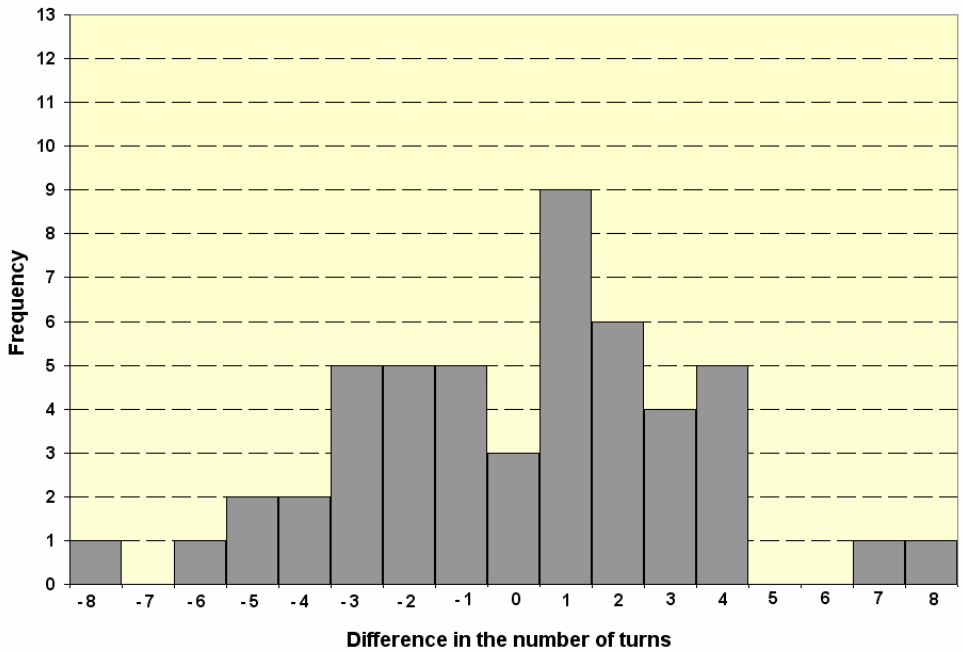

**(a) Specimen 1**




**(b) Specimen 2**




**(c) Specimen 3**




**(d) Specimen 4**

**Figure 6.10 Frequency histograms of the difference in the number of turns between the automated and manual methods**

### 6.4.3 Discussion

There were differences in the results obtained from using the automated method and the manual method to count the number of snarl turns. The means of the of snarl turn values were, in practical terms of measuring twist liveliness, not too dissimilar. It may be thought that the manual method produced more reliable results because standard deviations were substantially lower but it should be noted that the manual method had been extensively tested and optimised when originally developing the standard methodology. Therefore it may be considered that the variability in the automated results was mainly due to practical issues related to the image capture stage of the process. It is anticipated that further optimisation of the image acquisition unit part of the apparatus would have the potential to produce improvements in the results. Within the limitations of this study, it was not feasible to undertake a similar amount of optimisation of the practical aspects of the automated method as was possible for the manual method.

It can be seen from the results, for example in Table 6.2, that, in general, the automated method produces results with less variability for coarser yarns than for finer yarns. One explanation could be because coarser yarns will obviously have a wider cross sectional width compared to finer yarns thus a better yarn density profile can be obtained for further analysis. Consequently the peaks or oscillation within the density profile of the coarser yarn may be more accurately recognised. By improving the image available for capture and improving image resolution or magnification, better overall results for finer yarn counts may be obtained. The possibilities for improvement to the image acquisition stage may include the following:

- Reflections from the water bath walls and reduced visibility from the samples being immersed in water may have placed limitations on image quality. Design amendments to the water bath materials and placing the samples closer to the side of the bath may improve this aspect.
- Amendments to the light source, intensity and positioning may improve image quality.
- Using a different camera with a higher image resolution for finer yarns.

The manual method was based on testing 10 samples at a time but using the automated method and apparatus included in this study only allowed for 5 samples to be tested because of image capturing limitations. Undoubtedly these limitations could be overcome, for example by using 2 cameras, improved light sources etc, and it is anticipated that sufficient optimisation of the practical aspects of the apparatus should allow the automated method to be used for testing 10 samples at a time as for the manual method.

## 6.5 CONCLUSIONS

It was recognised that it would be useful and desirable to reduce testing time and reduce the amount of manual operation involved in the method to assess the yarn twist liveliness reported in Chapter 3. Therefore, an automated image based method to count the number of snarl turns when the yarn samples are submerged in the water bath has been proposed. The automated method was developed to provide an alternative to the manual method of determining the number of snarl turns by use of a twist tester.

This system firstly involved capturing an image of the test samples in the water bath. A number of aspects were carefully considered to standardise the image environment to produce suitable images for analysis. These included producing a closed chamber with a controlled illumination system. A CMOS camera with 6.3 mega pixels and a diffuse light source were found to produce the best image that could be further processed to extract the number of snarl turns.

After the image of the test samples had been captured, it was necessary to convert the image into a greyscale and then a binary image. Image analysis techniques were used for counting the number of snarl turns along a test sample captured in the image. An important characteristic curve for the identification of the yarn snarls was obtained from the binary image. This curve is called the yarn density profile and is defined as the yarn cross sectional width along its length. It was observed that the number of snarls could be obtained by locating the number of local maximal values in the yarn density profile. However, it was found that the density profile of the actual yarn sample as compared to the simulated sample was complex as it contained many “fake” maximal values due to noise. Therefore, a robust pattern recognition algorithm was proposed to accurately identify the peaks or oscillations within the yarn density profile of the actual yarn samples. It was found that by using Fast Fourier Transform (FFT) and Adaptive Orientated Orthogonal Projective Decomposition (AOP) algorithms the oscillations of the yarn density profile could be matched adaptively and accurately. This was achieved by decomposing the yarn density profile signal into a number of Gaussian functions. As each Gaussian function corresponded to half of a yarn snarl, the number of snarls was determined by counting the number of Gaussian functions used and dividing by two.

The automated image based method was tested by comparing the results of the method to the results obtained by the manual method of using a twist tester to count the number of snarls in the same test samples. It was found that the testing time of the automated method compared to the manual method can be reduced by as much as 50%. There was a good agreement between the mean values obtained from the two methods as the difference in the number of turns was relatively minor. However, the automated system generally had a larger variation in the results obtained. The automated method may be considered to have been tested in principle only and the results are sufficiently encouraging to conclude that, with further optimisation of the practical details, the method could be expected to produce results of similar reliability as the manual method.

Similarly, optimisation of the image acquisition unit and analysis procedures would be necessary to overcome some of the limitations of the current image capture system. For example, improvements are required in the image capture and analysis of samples of finer yarn counts and the current system is limited to the testing of greige or light coloured yarns only. For dyed yarns of dark colours further testing of the system and certain modifications such as changing the background of the water bath and further evaluation of the pattern recognition algorithm would be required.

# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS

It has long been recognised that twist liveliness is a property of spun yarn that contributes significantly to problems arising in post-spinning yarn processing and to the problem of fabric spirality. It is therefore important to be able to measure twist liveliness efficiently over a wide range of conditions with a sufficient degree of confidence in the results and to use a standard method of measurement. It is considered that, although previous measurement methods may have been adequate for the purposes for which they were proposed, most have some limitations and disadvantages that might restrict their use in general applications.

Therefore, the aim of the work described in this thesis has been to establish a robust methodology and apparatus for the measurement of twist liveliness of conventional and modified ring spun yarns. This then led to its application to assess the properties of the recently developed Nu-Torque singles ring yarns and to the establishment of models to predict the spirality of knitted fabrics from parameters including yarn twist liveliness and other contributing factors.

This chapter provides a brief summary of the results of the work and the conclusions that may be drawn from the findings. Remaining problems and possible further research work are also discussed.

## 7.1 SUMMARY AND CONCLUSIONS

### 7.1.1 Measurement of Twist Liveliness

#### 7.1.1.1 Methodology and apparatus to measure twist liveliness

After considering existing methods relevant to the evaluation of twist liveliness a methodology and Yarn Snarling Apparatus have been developed to measure twist liveliness by counting the number of snarl turns which form when the two ends of a length of spun yarn are brought together in a loop.

The apparatus and procedure were designed to overcome the disadvantages of previous methods and to meet the requirements for best practices recommended for such testing methodologies. The unique features of the resultant system are:

- The test procedure and measurement units have been selected and designed to correlate well with the actual problem of twist liveliness being evaluated.
- The system is capable of producing accurate results under both laboratory and industrial types of conditions
- The apparatus is robust, portable and user-friendly.

- The operation is relatively simple as unskilled operators can be trained in a very short time.
- The method is relatively fast as multiple samples can be prepared and tested in quick succession.

The methodology was optimised in order to ensure that test results would be an accurate and true representation of a spun yarn's property of measured twist liveliness. Examples of the optimisation are the inclusion of a pretension system to prevent the formation of localised snarls or kinks in a yarn sample during the preparation stage so that the test length of the samples is consistent; the use of dead weights to keep the yarn samples completely submerged in water in order to attain a fully relaxed state during the test; the deployment of a twist tester to accurately count the number of snarl turns.

#### 7.1.1.2 Automation of the twist liveliness measurement apparatus

The apparatus, as initially developed, used a manually operated twist tester to count the number of snarl turns which form in the yarn samples when under test. This performed well in producing accurate measurement results and was reasonably efficient. However, it was considered that there was room to increase efficiency and reduce an operator's manual input by automating this part of the procedure.

The automated procedure uses a digital image based system for evaluating the twist liveliness of the spun yarns by counting the number of snarl turns from an image of the yarn sample under test. Firstly images are captured using an image acquisition unit composed of the water bath in an enclosed chamber, a light source and a CMOS camera. The images of the test samples were subsequently transferred to a computer and converted into binary images. A yarn density profile was extracted from the binary image to obtain the important characteristic curve for the identification of the yarn snarls. Fast Fourier Transform and Adaptive Orientated Orthogonal Projective Decomposition algorithms were found to be capable of recognising the oscillations within the density profile. This was achieved by decomposing the yarn density profile signal into a number of Gaussian functions. As each Gaussian function corresponded to half of a yarn snarl, the number of snarls was determined by counting the number of Gaussian functions used and dividing by two.

An investigation was undertaken whereby yarn samples were tested using the automated image-capture based system and the results analysed in comparison with the previous manual method of using a twist tester. A statistical analysis found that the automated method, although sound, had somewhat greater variance in the results compared to the manual procedure. However the automated method may be considered to have been tested in principle only and the results are sufficiently encouraging to conclude that, with further optimisation of the practical details in obtaining the image capture, the method could be expected to produce results of similar reliability as the manual method.

It was found that the testing time could be reduced by approximately 50% if the automated system was used. This confirmed that the efficiency of the methodology could be enhanced.

#### 7.1.1.3 Evaluation of the methodology and apparatus

The accuracy and precision of the measurement system was evaluated by repeated testing of identical samples from a range of yarns both within the same laboratory (intra-laboratory) and between different laboratories (inter-laboratory) in accordance with the ASTM Standard E 691-05. A statistical analysis of the results showed that the source of the largest variances in the test is attributed to the expected variation in the levels of snarl turns of different yarn specimens. Only a negligible proportion of the variability was due to trial to trial repeatability and operator reproducibility which indicates independence of operator skill in use.

The methodology and apparatus was used extensively for the measurement of twist liveliness when conducting an investigation of Nu-Torque yarns and when producing the spirality prediction models as described below. These applications confirmed that, under practical conditions, the testing procedure could be carried out effectively and efficiently by operators of different educational and skill levels.

Therefore, from both the theoretical and the practical points of view, it has been found that the Yarn Snarling Apparatus and the recommended testing procedure can be used to make accurate and repeatable measurements of snarl turns of 100% cotton ring yarns and hence measure the twist liveliness of these yarns over a range of yarn counts. It may be considered that it is suitable for adoption as a standard method of measurement of twist liveliness in any future such investigations and for use in industry to, for example, assess and monitor yarn properties during the spinning process.

An application was made for a U.S. Patent to cover the methodology and apparatus developed under this study for the measurement of twist liveliness. The patent "Yarn Snarling Testing Apparatus and Method" No. 7,219,556 has subsequently been granted.

### 7.1.2 Twist Liveliness of a Modified Ring Spun Yarn

The developed testing methodology and apparatus has been used to evaluate various aspects of Nu-Torque singles ring yarns in comparison with conventional ring yarns.

Firstly the experiments revealed that although, as expected, the twist liveliness of Nu-Torque yarns is much lower than conventional yarns; the property follows a similar linear relationship with yarn twist at constant speed ratio.

It was also found that different qualities of cotton did not affect the twist liveliness of either the conventional or the Nu-Torque yarns. This finding indicates the potential of the Nu-Torque system to spin yarns from lower quality cotton with acceptable spinning ability and yarn quality whilst still reducing twist liveliness. This is due to its higher rate of migration and the reduced height of the spinning triangle compared with conventional yarns.

From an analysis of the changes in twist liveliness of Nu-Torque and conventional yarns from processes downstream to spinning it was found that the twist liveliness of both the yarns increased slightly when the yarn was wound on to a cone from a cop contradicting a finding from a previous researcher. With the application of wax during winding, the twist liveliness of both conventional and Nu-Torque yarns was not significantly different from the twist liveliness measured in the unwaxed state. Package dyeing significantly reduced the twist liveliness of the conventional yarn but not the twist liveliness of the Nu-Torque yarn. By the introduction of the false twisting operation in the Nu-Torque system the yarn produced has different fibre and yarn configurations compared to the conventionally spun ring yarns and it is these modifications that account for the differences in the twist liveliness.

Finally, an analysis of the performance and capability of the Nu-Torque system to produce knitting yarns with reduced twist liveliness revealed that, during a small scale production trial, the system is in control. The process is estimated to have a medium capability if the upper specification limit for twist liveliness is set at 25turns/25cm indicating good potential for the commercialisation of the Nu-Torque system for producing a novel ring spun yarn.

### 7.1.4 Models for the Prediction of Fabric Spirality

The contribution of twist liveliness to the degree of fabric spirality is well known. Nevertheless, no systematic investigations have been carried out previously to quantify such effect. In this work, the developed testing methodology and apparatus has been applied to study, for the first time, the quantitative relationship between yarn twist liveliness and fabric spirality. Additional parameters that contribute to the degree of spirality such as tightness factor, number of feeders, machine rotational direction, gauge and piece dyeing were also incorporated into the analysis.

Predictive mathematical models were produced based on a regression technique and on an Artificial Neural Network approach. Investigations were conducted for both dry relaxed and wash and dry relaxed fabrics but it was established that spirality could not be predicted with any reasonable degree of accuracy when using fabric samples in their dry relaxation state. The models are based on wash and dry relaxed fabrics only.

The results of initial simple bivariate and partial analyses demonstrated that twist liveliness is significantly correlated with fabric spirality whereas tightness factor has a moderately negative correlation. The other parameters have a less important effect on fabric spirality.

For the first model, a regressional equation for the angle of spirality was derived by a stepwise multiple regression technique. The regression analyses can reveal the quantitative relationship between the angle of spirality and the twist liveliness and tightness factor. It showed that approximately 63% of the variance in the fabric spirality of the specimens tested is explained by yarn twist liveliness alone. With the inclusion of tightness factor, about 93% of the variance of fabric spirality can be explained.

The second model used an Artificial Neural Networks approach, which is an information processing tool inspired by biological neural networks and which, until now, has not been applied for predicting the degree of fabric spirality. This study has shown that such a method of analysis is suitable for the purpose and the neural network model selected was a feedforward backpropagation model. Sixty data sets were used for training and testing different neural network structures using a Levenberg-Marquardt algorithm. According to the investigations, a model with one hidden layer, 18 hidden neurons, a tansig transfer function in the hidden layer and a single linear neuron in the output layer had the best performance.

The derived regressional equation and established neural network model were tested on data that was not used for model development or training. It was found that there was a relatively good agreement between the measured angle of spirality of the fabric samples and both of the models' predicted values. However, the neural network model predicted the angle of spirality with a slightly better degree of accuracy as compared to the regression model.

Although both approaches could help to predict fabric spirality, the statistical approach is well founded. It provides a clear understanding of the influence of the input parameters, twist liveliness and tightness factor, on the degree of spirality after wash and dry relaxation and allows for the exploration of the interrelationships of these factors step by step. For instance, the percentage of variance of the factors as an indication of their contribution toward the fabric spirality is known. On the other hand, the artificial neural network approach is a fast predictive tool with self-learning capabilities and with the flexibility to suit further development.

Overall it can be concluded that the application of the results obtained from the measurement of twist liveliness using the developed methodology and apparatus is effective in the prediction of fabric spirality after wash and dry relaxation processes using either the statistical or the artificial neural network approach.

## 7.2 RECOMMENDATIONS FOR FUTURE WORK

The major objectives of the research project have been achieved, which has established a good foundation for further investigations. Possible future work is suggested as follows.

The developed Yarn Snarling Apparatus has been proven to be effective and efficient in accurately measuring the twist liveliness of spun yarns and currently two textile mills possess the apparatus. However minor refinements to the design and construction may improve its functional performance such as the inclusion of a yarn guide and tensioning device to guide the yarn from the package holder to the yarn clamp; using a digital pretension meter and adding a drainage feature to the water tank.

The inclusion in the Apparatus of an image processing technique has been shown to be a very useful tool for counting the number of snarl turns of the yarn samples and reducing the testing time. However, further development would be beneficial to improve the accuracy of the results and to ensure that the system could be used in both laboratory and industrial settings successfully. Firstly the investigation would probably focus on improving the image acquisition unit in order to optimise the image-capture quality thus finer yarn counts could be more accurately evaluated.

This may involve practical aspects such as:

- Design amendments to the water bath materials and to position the samples closer to the side of the bath.
- Amendments to the light source, intensity and positioning.
- Use of a different camera or another type of image capturing method such as laser scanning.

The investigation could then be extended by testing the ability of the image based system to evaluate the number of snarl turns of dyed yarn samples and this may involve modifying the background colour of the water bath.

Finally, a computer programme might be written to produce a user-friendly interface to allow operators to easily input the details of the samples and to access the results.

In the development of the testing methodology, limitations of time and resources restricted the investigations to the study of only 100% cotton ring yarns in this research project. For further investigations, it would be recommended to study and, if necessary, optimise the test procedure to measure the twist liveliness of yarns spun by different spinning systems as well as yarns produced from different fibre types such as wool. One reason to study ring spun yarns produced from wool is because they also exhibit high twist liveliness. Also the method of using the Nu-Torque system to reduce the twist liveliness of worsted singles ring yarns is currently being conducted and preliminary tests have shown that the apparatus could effectively measure the twist liveliness of these yarns after modifying the testing variables i.e. the pretension and dead weight. Further experiments to determine the testing variables over a range of yarn counts and the consideration of aspects such as the effects of detergents in the water bath on the twist liveliness of the yarns would be necessary.

There is a highly significant correlation between the degree of spirality predicted by the models and the actual measured values of spirality of the fabrics knitted from the yarns under test. Recommendations for future work to enhance the findings would be to extend the coverage by inserting more new data sets (containing both input and output variables) into the models. This would require assessing a wider range of fabrics produced from different types of yarns and yarn counts in order to obtain more new data. At the same time, it is suggested it would be necessary to make sure that the values of the output variables are evenly distributed within the normal range. Afterwards, the improved models may be incorporated into a computer programme to build an intelligent system to allow manufacturers to access the information conveniently and easily by means of a user-friendly interface. This system would have the potential to assist fabric manufacturers in selecting the most appropriate parameters in order to minimise fabric spirality.

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# APPENDICES

# APPENDIX 3.1

# YARN SNARLING APPARATUS AND PROCEDURE

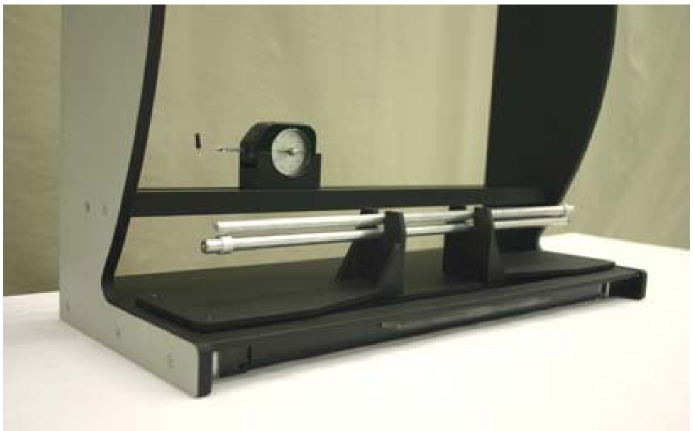
## (A) The Apparatus

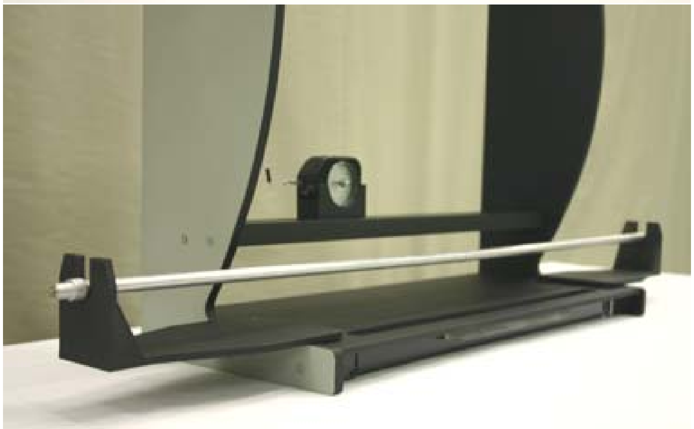
The Yarn Snarling Apparatus comprises the following parts:

- One mainframe (including a drawer)

- Yarn sample holder

- One specimen holder for a cop





- One specimen holder for a cone

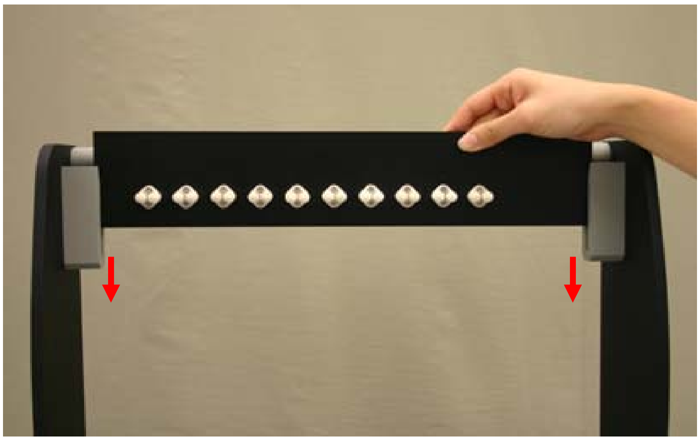
- One water tank and holder

- One set of dead weights

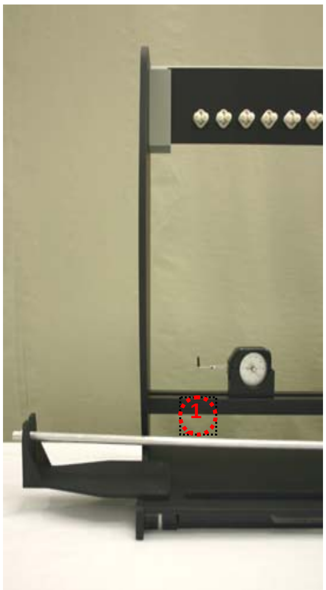
**(B) Testing Procedure**

- **Specimen preparation**

(1) The yarn sample holder is inserted into the slots on the yarn snarling apparatus.

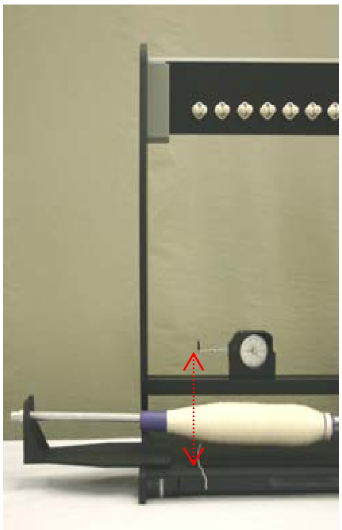


(2) The yarn package is inserted onto the corresponding yarn specimen holder

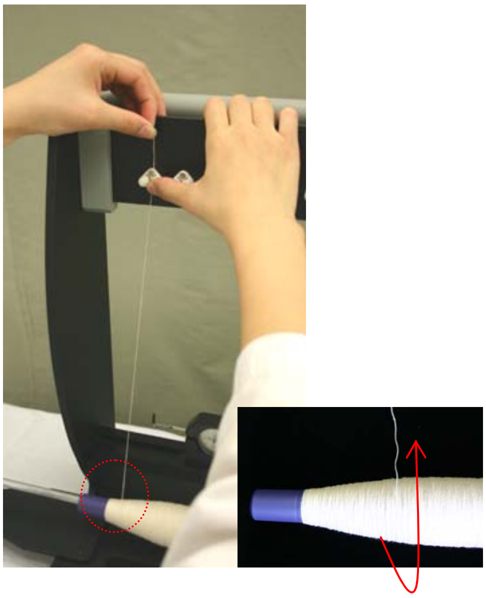



(3) The tension meter is moved to position one.

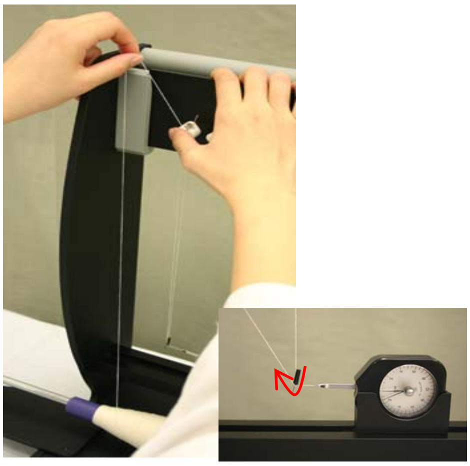
(4) The yarn package is moved in line with the pretension meter starting with position one



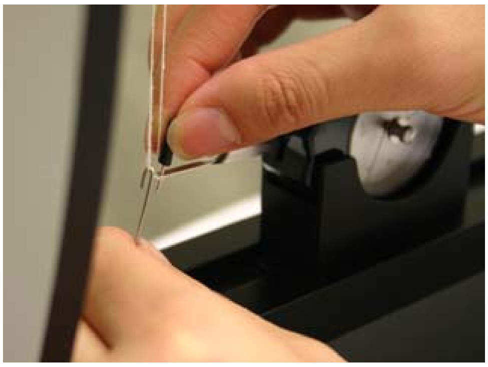
(5) The end of the yarn sample is drawn longitudinally and with minimal tension towards the right yarn clamp, the yarn end is fixed, leaving a minimum of 2cm free end



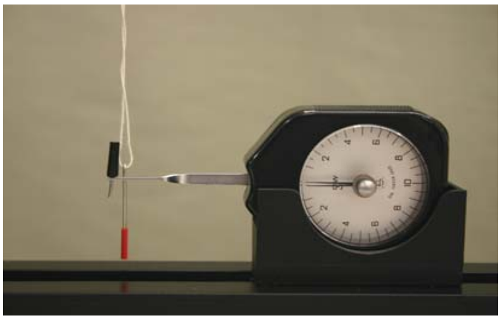
(6) The yarn sample is drawn continuously from the yarn package around the tension meter and up towards the left yarn clamp, the second yarn end is fixed and cut leaving a minimum of 2cm free end. The yarn pretension is adjusted.



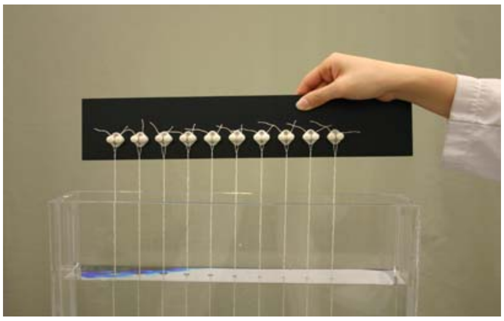
(7) A dead weight is hooked onto the yarn sample and the yarn is simultaneously released from the tension meter by lifting up the thin rod the yarn is hooked around on the tension meter.



The sample is allowed to rotate freely.

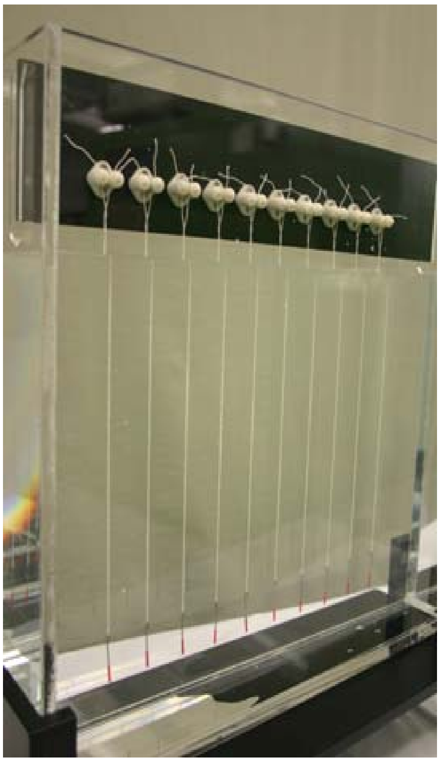


(8) The yarn sample holder is removed from the snarling apparatus and placed into the slots in the water bath.



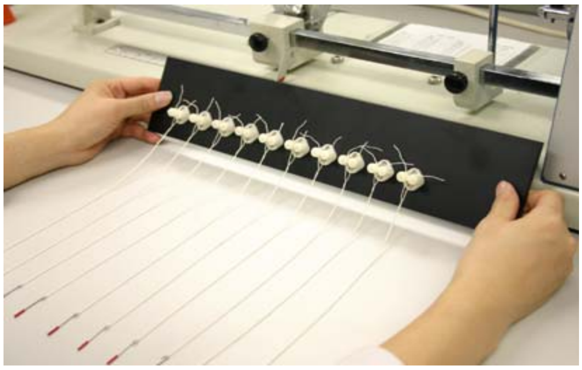
(9) Sufficient time is allowed for the yarn to reach the maximum snarling potential i.e. no rotational movement (approximately 3 minutes).

The yarn sample holder is then removed from the water bath.



- **Snarl turn determination: manual method using a standard twist tester**

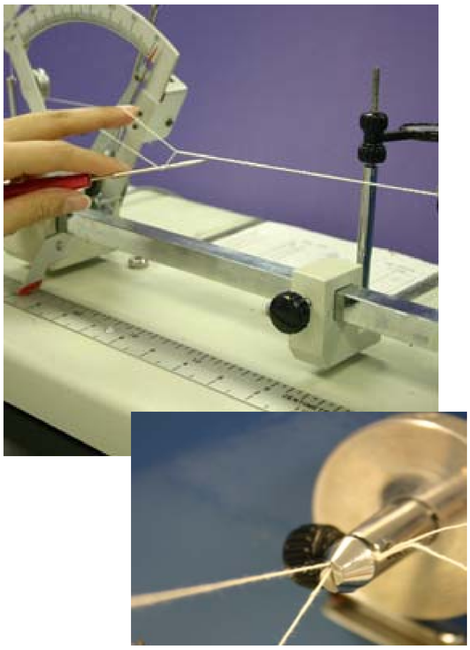
(12) The sample holder containing the yarn samples is placed in front of the twist tester.
*(Requirements of the twist tester: operated manually or electronically, S or Z direction depending on the direction of the snarls, clamps set 25 cm apart, 5g pretension if available.)*



(13) The end of yarn sample is hooked onto the twist tester and the dead weight removed.

The other end of yarn sample is pulled out from the clamping element and fixed to the opposite clamp on the twist tester.

(14) The yarn samples are untwisted until no snarls remained. The number of snarl turns within a 25cm length are recorded.



## (C) Dead Weights and Pretensions

For 100% cotton yarn the following guidelines are used to choose the dead weight and pretension.

| Yarn Count Range (Ne) | Dead Weight (g) | Visual Reference |
|---|---|---|
| Above 32 | 0.06 |  |
| 31.9 – 20 | 0.10 |  |
| 19.9 – 16 | 0.15 |  |
| 15.9 – 11 | 0.20 |  |
| 10.9 – 7 | 0.30 |  |
| 6.9 – 4 | 0.50 |  |
| Below 4 | 1.00 |  |

| Yarn Count Range (Ne) | Pretension (g) |
|---|---|
| Above 32 | 1 |
| 31.9 – 20 | 1 |
| 19.9 – 16 | 2 |
| 15.9 – 11 | 4 |
| 10.9 – 7 | 4 |
| 6.9 – 4 | 5 |
| Below 4 | 8 |

# APPENDIX 4.1

# TWIST LIVELINESS RESULTS:

# COMPARISON BETWEEN CONVENTIONAL AND

# NU-TORQUE YARNS

**(A) Influence of Yarn Twist**

Conventional Singles Ring Yarn (29.5tex, 100% Cotton)

| Sample No. | **Number of snarl turns/25cm** | | | |
|---|---|---|---|---|
| | **Twist Multiple** | | | |
| | **2.5** | **2.8** | **3.0** | **3.6** |
| 1 | 35 | 42 | 47 | 52 |
| 2 | 40 | 41 | 47 | 55 |
| 3 | 37 | 43 | 44 | 52 |
| 4 | 32 | 46 | 52 | 52 |
| 5 | 37 | 39 | 48 | 55 |
| 6 | 35 | 45 | 42 | 54 |
| 7 | 35 | 42 | 47 | 52 |
| 8 | 39 | 44 | 46 | 53 |
| 9 | 35 | 41 | 49 | 54 |
| 10 | 41 | 41 | 44 | 53 |
| 11 | 36 | 40 | 50 | 54 |
| 12 | 42 | 42 | 45 | 53 |
| 13 | 40 | 40 | 46 | 56 |
| 14 | 33 | 42 | 44 | 51 |
| 15 | 37 | 41 | 41 | 52 |
| 16 | 38 | 40 | 46 | 53 |
| 17 | 37 | 42 | 45 | 50 |
| 18 | 38 | 41 | 45 | 57 |
| 19 | 38 | 40 | 44 | 53 |
| 20 | 39 | 43 | 42 | 59 |
| 21 | 31 | 40 | 45 | 60 |
| 22 | 40 | 42 | 47 | 49 |
| 23 | 34 | 43 | 47 | 53 |

| | | | | |
|---|---|---|---|---|
| 24 | 30 | 40 | 41 | 57 |
| 25 | 34 | 42 | 46 | 50 |
| 26 | 31 | 41 | 46 | 58 |
| 27 | 39 | 40 | 45 | 58 |
| 28 | 36 | 43 | 45 | 53 |
| 29 | 30 | 41 | 38 | 58 |
| 30 | 33 | 44 | 45 | 49 |
| **Mean** | **36** | **42** | **45** | **53** |
| **CV%** | 9.2 | 3.9 | 6.1 | 5.5 |

Nu-Torque Singles Ring Yarn (29.5tex, 100% Cotton, Speed ratio 0.56)

| Sample No. | Number of snarl turns/25cm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Twist Multiple** | | | | | | | |
| | **1.7** | **1.9** | **2.1** | **2.3** | **2.5** | **2.7** | **3.0** | **3.4** |
| 1 | 21 | 20 | 27 | 26 | 29 | 31 | 33 | 35 |
| 2 | 21 | 22 | 21 | 26 | 28 | 32 | 31 | 31 |
| 3 | 20 | 23 | 23 | 21 | 29 | 31 | 33 | 36 |
| 4 | 21 | 21 | 21 | 25 | 31 | 31 | 31 | 30 |
| 5 | 22 | 23 | 21 | 26 | 31 | 33 | 29 | 31 |
| 6 | 19 | 21 | 21 | 27 | 31 | 29 | 29 | 32 |
| 7 | 20 | 22 | 26 | 23 | 28 | 32 | 33 | 30 |
| 8 | 21 | 21 | 22 | 25 | 30 | 32 | 33 | 36 |
| 9 | 22 | 21 | 26 | 22 | 26 | 32 | 31 | 34 |
| 10 | 21 | 24 | 23 | 27 | 29 | 28 | 34 | 36 |
| 11 | 22 | 20 | 21 | 26 | 29 | 31 | 31 | 34 |
| 12 | 20 | 24 | 22 | 25 | 30 | 30 | 29 | 35 |
| 13 | 19 | 21 | 23 | 28 | 26 | 32 | 28 | 32 |
| 14 | 21 | 20 | 28 | 22 | 25 | 31 | 32 | 37 |
| 15 | 21 | 22 | 22 | 28 | 27 | 30 | 31 | 37 |
| 16 | 20 | 21 | 25 | 24 | 32 | 25 | 33 | 38 |
| 17 | 19 | 18 | 23 | 21 | 31 | 29 | 32 | 32 |
| 18 | 20 | 23 | 24 | 27 | 27 | 32 | 36 | 31 |
| 19 | 20 | 19 | 24 | 27 | 23 | 30 | 30 | 35 |
| 20 | 21 | 24 | 26 | 24 | 28 | 33 | 30 | 32 |
| 21 | 21 | 19 | 26 | 24 | 25 | 32 | 31 | 30 |
| 22 | 18 | 22 | 22 | 24 | 26 | 27 | 40 | 31 |
| 23 | 20 | 20 | 26 | 24 | 30 | 31 | 30 | 34 |
| 24 | 20 | 23 | 25 | 28 | 28 | 31 | 38 | 33 |
| 25 | 20 | 23 | 24 | 28 | 25 | 33 | 34 | 30 |
| 26 | 20 | 23 | 22 | 25 | 25 | 28 | 32 | 33 |
| 27 | 21 | 23 | 24 | 23 | 25 | 29 | 31 | 41 |
| 28 | 20 | 21 | 26 | 26 | 28 | 33 | 35 | 30 |
| 29 | 19 | 24 | 25 | 25 | 26 | 27 | 32 | 35 |
| 30 | 20 | 19 | 22 | 25 | 27 | 27 | 33 | 34 |
| **Mean** | **20** | **22** | **24** | **25** | **28** | **30** | **32** | **34** |
| **CV%** | 4.7 | 7.9 | 8.7 | 8.1 | 8.3 | 6.9 | 8.2 | 8.3 |

**(B) Influence of Fibre Quality**

Conventional Singles Ring Yarn (29.5tex, 100% Cotton)

| Sample No. | Number of snarl turns/25cm | | | |
|---|---|---|---|---|
| | Fibre type | | | |
| | American + Australian | American + Sudan | Ivory Coast | Pima |
| 1 | 58 | 55 | 61 | 53 |
| 2 | 57 | 55 | 63 | 54 |
| 3 | 58 | 59 | 63 | 58 |
| 4 | 58 | 54 | 59 | 53 |
| 5 | 57 | 62 | 62 | 59 |
| 6 | 56 | 55 | 61 | 54 |
| 7 | 55 | 57 | 59 | 58 |
| 8 | 52 | 57 | 59 | 58 |
| 9 | 58 | 52 | 61 | 59 |
| 10 | 54 | 58 | 58 | 60 |
| 11 | 56 | 56 | 60 | 54 |
| 12 | 60 | 57 | 58 | 58 |
| 13 | 64 | 54 | 54 | 58 |
| 14 | 60 | 59 | 53 | 53 |
| 15 | 62 | 51 | 59 | 59 |
| 16 | 55 | 55 | 59 | 60 |
| 17 | 59 | 55 | 54 | 54 |
| 18 | 61 | 55 | 58 | 59 |
| 19 | 60 | 56 | 52 | 59 |
| 20 | 58 | 52 | 60 | 58 |
| 21 | 60 | 59 | 61 | 53 |
| 22 | 55 | 55 | 60 | 53 |
| 23 | 63 | 56 | 58 | 54 |
| 24 | 58 | 56 | 57 | 58 |
| 25 | 54 | 53 | 65 | 59 |
| 26 | 60 | 57 | 58 | 60 |
| 27 | 56 | 51 | 62 | 58 |
| 28 | 60 | 60 | 62 | 53 |
| 29 | 64 | 55 | 59 | 58 |
| 30 | 53 | 57 | 62 | 54 |
| **Mean** | **58** | **56** | **59** | **57** |
| **CV%** | 5.4 | 4.6 | 5.1 | 4.7 |

Nu-Torque Singles Ring Yarn (29.5tex, 100% Cotton)

| Sample No. | Number of snarl turns/25cm | | | |
|---|---|---|---|---|
| | Fibre type | | | |
| | American + Australian | American + Sudan | Ivory Coast | Pima |
| 1 | 21 | 20 | 20 | 19 |
| 2 | 19 | 21 | 21 | 17 |
| 3 | 23 | 23 | 16 | 20 |
| 4 | 21 | 19 | 19 | 16 |
| 5 | 22 | 21 | 21 | 17 |
| 6 | 18 | 22 | 18 | 17 |
| 7 | 21 | 22 | 19 | 16 |
| 8 | 22 | 22 | 17 | 15 |
| 9 | 24 | 23 | 20 | 24 |
| 10 | 20 | 21 | 18 | 16 |
| 11 | 19 | 20 | 19 | 17 |
| 12 | 18 | 21 | 21 | 20 |
| 13 | 19 | 22 | 21 | 18 |
| 14 | 18 | 24 | 20 | 15 |
| 15 | 19 | 17 | 23 | 18 |
| 16 | 17 | 24 | 20 | 24 |
| 17 | 18 | 24 | 19 | 18 |
| 18 | 14 | 22 | 20 | 19 |
| 19 | 17 | 19 | 19 | 21 |
| 20 | 15 | 22 | 19 | 19 |
| 21 | 21 | 20 | 17 | 21 |
| 22 | 17 | 21 | 16 | 18 |
| 23 | 16 | 22 | 16 | 23 |
| 24 | 20 | 21 | 18 | 20 |
| 25 | 23 | 22 | 17 | 20 |
| 26 | 21 | 22 | 20 | 19 |
| 27 | 21 | 22 | 18 | 21 |
| 28 | 22 | 20 | 19 | 24 |
| 29 | 18 | 20 | 14 | 18 |
| 30 | 22 | 20 | 17 | 22 |
| **Mean** | **20** | **21** | **19** | **19** |
| **CV%** | 12.7 | 7.4 | 10.3 | 13.6 |

**(C) Influence of Processes Subsequent to Spinning**

Conventional Singles Ring Yarn (29.5tex, 100% Cotton)

| Sample No. | Number of snarl turns/25cm | | | |
|---|---|---|---|---|
| | Cop | Cone | Cone (waxed) | Cone (package dyed) |
| 1 | 55 | 52 | 48 | 28 |
| 2 | 54 | 56 | 52 | 39 |
| 3 | 53 | 57 | 55 | 32 |
| 4 | 55 | 53 | 55 | 34 |
| 5 | 53 | 53 | 51 | 29 |
| 6 | 54 | 57 | 51 | 35 |
| 7 | 58 | 57 | 48 | 37 |
| 8 | 54 | 55 | 49 | 32 |
| 9 | 56 | 56 | 54 | 33 |
| 10 | 54 | 53 | 51 | 35 |
| 11 | 55 | 56 | 53 | 34 |
| 12 | 52 | 56 | 53 | 36 |
| 13 | 53 | 58 | 50 | 34 |
| 14 | 50 | 57 | 50 | 36 |
| 15 | 52 | 58 | 55 | 32 |
| 16 | 56 | 55 | 56 | 40 |
| 17 | 51 | 56 | 54 | 38 |
| 18 | 55 | 57 | 53 | 29 |
| 19 | 54 | 58 | 56 | 32 |
| 20 | 48 | 60 | 55 | 35 |
| 21 | 52 | 48 | 58 | 33 |
| 22 | 54 | 51 | 59 | 34 |
| 23 | 55 | 50 | 53 | 38 |
| 24 | 54 | 50 | 57 | 33 |
| 25 | 52 | 49 | 57 | 31 |
| 26 | 53 | 55 | 53 | 39 |
| 27 | 53 | 53 | 55 | 29 |
| 28 | 57 | 51 | 57 | 40 |
| 29 | 55 | 52 | 57 | 28 |
| 30 | 55 | 48 | 51 | 37 |
| **Mean** | **53** | **54** | **53** | **34** |
| **CV%** | 3.8 | 6.0 | 5.6 | 10.3 |

Nu-Torque Singles Ring Yarn (29.5tex, 100% Cotton)

| Sample No. | **Number of snarl turns/25cm** | | | |
|---|---|---|---|---|
| | Cop | Cone | Cone (waxed) | Cone (package dyed) |
| 1 | 22 | 19 | 19 | 17 |
| 2 | 21 | 25 | 20 | 18 |
| 3 | 19 | 25 | 19 | 20 |
| 4 | 20 | 25 | 17 | 18 |
| 5 | 20 | 24 | 20 | 16 |
| 6 | 20 | 21 | 24 | 20 |
| 7 | 20 | 20 | 19 | 20 |
| 8 | 21 | 23 | 19 | 18 |
| 9 | 20 | 20 | 20 | 17 |
| 10 | 21 | 21 | 18 | 17 |
| 11 | 21 | 27 | 18 | 16 |
| 12 | 18 | 24 | 15 | 18 |
| 13 | 19 | 25 | 19 | 19 |
| 14 | 18 | 19 | 22 | 18 |
| 15 | 17 | 23 | 23 | 17 |
| 16 | 17 | 28 | 16 | 18 |
| 17 | 20 | 23 | 17 | 16 |
| 18 | 21 | 22 | 21 | 17 |
| 19 | 18 | 21 | 24 | 21 |
| 20 | 17 | 25 | 20 | 19 |
| 21 | 18 | 16 | 22 | 20 |
| 22 | 19 | 20 | 19 | 20 |
| 23 | 18 | 21 | 21 | 16 |
| 24 | 18 | 22 | 15 | 17 |
| 25 | 21 | 19 | 17 | 19 |
| 26 | 20 | 22 | 19 | 20 |
| 27 | 17 | 27 | 23 | 19 |
| 28 | 21 | 23 | 20 | 23 |
| 29 | 19 | 19 | 23 | 20 |
| 30 | 17 | 21 | 23 | 19 |
| **Mean** | **19** | **22** | **20** | **19** |
| **CV%** | 7.9 | 12.6 | 12.8 | 10.0 |

# APPENDIX 4.2

## NU-TORQUE YARN PRODUCTION TRIAL RESULTS

| Lot No. | Observation (No. of snarl turns/25cm) | | | | Mean | Std. Dev. | Range |
|---|---|---|---|---|---|---|---|
| 1 | **18** | **22** | **20** | **20** | 20 | 1.63 | 4 |
| 2 | **18** | **23** | **20** | **20** | 20 | 2.06 | 5 |
| 3 | **22** | **20** | **21** | **21** | 21 | 0.82 | 2 |
| 4 | **23** | **19** | **21** | **20** | 21 | 1.71 | 4 |
| 5 | **23** | **18** | **22** | **17** | 20 | 2.94 | 6 |
| 6 | **19** | **19** | **21** | **19** | 20 | 1.00 | 2 |
| 7 | **20** | **22** | **21** | **20** | 21 | 0.96 | 2 |
| 8 | **19** | **19** | **20** | **20** | 20 | 0.58 | 1 |
| 9 | **19** | **20** | **17** | **18** | 19 | 1.29 | 3 |
| 10 | **18** | **20** | **19** | **17** | 19 | 1.29 | 3 |
| 11 | **20** | **20** | **19** | **21** | 20 | 0.82 | 2 |
| 12 | **18** | **18** | **17** | **21** | 19 | 1.73 | 4 |
| 13 | **23** | **21** | **22** | **20** | 22 | 1.29 | 3 |
| 14 | **22** | **20** | **17** | **18** | 19 | 2.22 | 5 |
| 15 | **17** | **17** | **18** | **17** | 17 | 0.50 | 1 |
| 16 | **22** | **19** | **19** | **20** | 20 | 1.41 | 3 |
| 17 | **17** | **20** | **16** | **22** | 19 | 2.75 | 6 |
| 18 | **19** | **17** | **17** | **15** | 17 | 1.63 | 4 |
| 19 | **17** | **19** | **20** | **18** | 19 | 1.29 | 3 |
| 20 | **21** | **19** | **21** | **18** | 20 | 1.50 | 3 |
| 21 | **18** | **18** | **17** | **15** | 17 | 1.41 | 3 |
| | | | | Totals | 406.25 | - | 69 |

# APPENDIX 5.1

# INPUT AND OUTPUT VARIABLES FOR THE DEVELOPMENT OF MODELS TO PREDICT SPIRALITY

| Sample No. | Input variables | | | | | | Output variables | |
|---|---|---|---|---|---|---|---|---|
| | **Twist liveliness** (turns/25cm) | **Number of feeders** | **Gauge** | **Rotational direction** | **Piece dyed** | **Tightness Factor** | **Measured angle of spirality (degrees)** After wash & dry relaxation | **Measured angle of spirality (degrees)** After dry relaxation |
| 1 | 46 | 1 | 2 | 1 | 0 | 12.82 | 26.73 | 13.96 |
| 2 | 46 | 1 | 2 | 1 | 0 | 13.93 | 18.97 | 9.97 |
| 3 | 46 | 1 | 2 | 1 | 0 | 16.63 | 12.6 | 8.58 |
| 4 | 61 | 1 | 2 | 1 | 0 | 13.72 | 20.37 | 12.86 |
| 5 | 61 | 1 | 2 | 1 | 0 | 16.37 | 18.06 | 10.25 |
| 6 | 45 | 1 | 2 | 1 | 0 | 16.7 | 6.85 | 4.63 |
| 7 | -30 | 1 | 2 | 1 | 0 | 16.7 | -5.94 | -8.4 |
| 8 | 21 | 1 | 2 | 1 | 0 | 16.74 | 2.19 | 0 |
| 9 | 30 | 1 | 2 | 1 | 0 | 16.7 | 3.56 | 0.73 |
| 10 | 22 | 1 | 2 | 1 | 0 | 16.7 | 3.18 | 0.65 |
| 11 | 36 | 2 | 1 | 0 | 0 | 16.16 | 7.3 | 5.09 |
| 12 | 21 | 2 | 1 | 0 | 0 | 16.23 | 5.84 | 4.63 |
| 13 | 61 | 2 | 1 | 0 | 0 | 17.03 | 10.18 | 8.56 |
| 14 | 60 | 3 | 3 | 0 | 0 | 17.03 | 11.13 | 10.01 |
| 15 | 52 | 3 | 3 | 0 | 0 | 16.96 | 8.54 | 6.58 |
| 16 | -17 | 3 | 3 | 0 | 0 | 17.09 | -2.03 | 2.36 |
| 17 | 54 | 3 | 3 | 0 | 0 | 16.81 | 8.57 | 6.75 |
| 18 | 54 | 3 | 3 | 0 | 0 | 16.95 | 5.58 | 5.91 |
| 19 | -7 | 3 | 3 | 0 | 0 | 16.9 | -1.54 | 2.34 |
| 20 | -10 | 3 | 3 | 0 | 0 | 16.83 | -2.27 | 1.67 |
| 21 | 21 | 3 | 3 | 0 | 0 | 17.11 | 3.86 | 6.24 |
| 22 | 20 | 3 | 3 | 0 | 0 | 17.17 | 2.09 | 2.77 |
| 23 | 22 | 3 | 3 | 0 | 0 | 17.18 | 2.41 | 1.21 |
| 24 | 60 | 3 | 3 | 1 | 0 | 17.03 | 12.79 | 8.75 |
| 25 | 52 | 3 | 3 | 1 | 0 | 16.96 | 10.5 | 5.95 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 26 | -17 | 3 | 3 | 1 | 0 | 17.09 | -2.56 | -2.23 |
| 27 | 54 | 3 | 3 | 1 | 0 | 16.81 | 10.11 | 5.36 |
| 28 | 54 | 3 | 3 | 1 | 0 | 16.95 | 8.96 | 4 |
| 29 | -7 | 3 | 3 | 1 | 0 | 16.9 | -1.82 | -0.8 |
| 30 | -10 | 3 | 3 | 1 | 0 | 16.83 | -1.06 | 1.36 |
| 31 | 21 | 3 | 3 | 1 | 0 | 17.11 | 5 | 2.49 |
| 32 | 20 | 3 | 3 | 1 | 0 | 17.17 | 1.13 | 1.26 |
| 33 | 22 | 3 | 3 | 1 | 0 | 17.18 | 2.05 | -0.5 |
| 34 | 21 | 3 | 3 | 0 | 1 | 16.96 | 4.45 | 3.34 |
| 35 | 60 | 3 | 3 | 0 | 1 | 16.96 | 7.92 | 7.46 |
| 36 | 52 | 3 | 3 | 0 | 1 | 16.96 | 7.99 | 5.4 |
| 37 | -17 | 3 | 3 | 0 | 1 | 16.96 | -2.15 | -1.61 |
| 38 | 20 | 3 | 3 | 0 | 1 | 16.96 | 2.07 | 1.38 |
| 39 | 54 | 3 | 3 | 0 | 1 | 16.96 | 6.84 | 5.29 |
| 40 | -7 | 3 | 3 | 0 | 1 | 16.96 | -2.12 | -2.49 |
| 41 | 54 | 3 | 3 | 0 | 1 | 16.96 | 6.58 | 4.47 |
| 42 | -10 | 3 | 3 | 0 | 1 | 16.96 | -2.87 | -2.91 |
| 43 | 22 | 3 | 3 | 0 | 1 | 16.96 | 2.29 | -0.57 |
| 44 | 21 | 3 | 3 | 1 | 1 | 17.03 | 3.92 | 2.68 |
| 45 | 60 | 3 | 3 | 1 | 1 | 17.03 | 7.11 | 6.53 |
| 46 | 52 | 3 | 3 | 1 | 1 | 17.03 | 7.67 | 6.66 |
| 47 | -17 | 3 | 3 | 1 | 1 | 17.03 | -2.05 | 1.2 |
| 48 | 20 | 3 | 3 | 1 | 1 | 17.03 | 2.03 | 2.34 |
| 49 | 54 | 3 | 3 | 1 | 1 | 17.03 | 7.2 | 4.48 |
| 50 | -7 | 3 | 3 | 1 | 1 | 17.03 | -2.49 | -1.95 |
| 51 | 54 | 3 | 3 | 1 | 1 | 17.03 | 5.23 | 3.5 |
| 52 | -10 | 3 | 3 | 1 | 1 | 17.03 | -3.68 | -4.33 |
| 53 | 22 | 3 | 3 | 1 | 1 | 17.03 | 3.17 | 2.04 |
| 54 | 20 | 3 | 3 | 1 | 0 | 17.03 | 0.7 | -1.51 |
| 55 | 34 | 3 | 3 | 1 | 0 | 17.03 | 7.64 | 2.23 |
| 56 | 0 | 3 | 3 | 1 | 0 | 17.03 | -1.82 | -2.12 |
| 57 | 35 | 3 | 3 | 1 | 0 | 17.03 | 5.45 | 1.8 |
| 58 | -1 | 3 | 3 | 1 | 0 | 17.03 | -3.76 | -3.01 |
| 59 | 19 | 3 | 3 | 1 | 0 | 17.03 | 2.45 | -2.19 |
| 60 | 20 | 3 | 3 | 1 | 0 | 17.03 | 1.56 | 0.44 |

# APPENDIX 5.2

# PROGRAM FOR PREDICTION OF SPIRALITY BASED ON BACK PROPAGATION NEURAL NETWORK

```
p=[46,46,46,61,61,45,-30,21,30,22,36,21,61,60,52,-
17,54,54,-7,-10,
21,20,22,60,52,-17,54,54,-7,-10,21,20,22,21,60,52,-
17,20,54,-7,54,-10,
22,21,60,52,-17,20,54,-7,54,-10,22,20,34,0,35,-1,19,20;
1,1,1,1,1,1,1,1,1,1,2,2,2,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,
3,3,3,3,3,3,
3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3;
2,2,2,2,2,2,2,2,2,2,1,1,1,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,
3,3,3,3,3,3,3,3,3,
3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3;
1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,
1,1,1,1,0,0,0,0,0,
0,0,0,0,0,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1;
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,1,1,
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0;
12.82,13.93,16.63,13.72,16.37,16.7,16.7,16.74,16.7,16.7,16
.16,16.23,
17.03,17.03,16.96,17.09,16.81,16.95,16.9,16.83,17.11,17.17
,17.18,17.03,
16.96,17.09,16.81,16.95,16.9,16.83,17.11,17.17,17.18,16.96
,16.96,16.96,
16.96,16.96,16.96,16.96,16.96,16.96,16.96,17.03,17.03,17.0
3,17.03,17.03,
17.03,17.03,17.03,17.03,17.03,17.03,17.03,17.03,17.03,17.0
3,17.03,17.03;];

t=[26.73,18.97,12.6,20.37,18.06,6.85,5.94,2.19,3.56,3.18,7
.3,5.84,10.18,
```

```
11.13,8.54,-2.03,8.57,5.58,-1.54,-
2.27,3.86,2.09,2.41,12.79,10.5,-2.56,10.11,8.96,-1.82,-
1.06,5,1.13,2.05,4.45,7.92,7.99,-2.15,2.07,6.84,-
2.12,6.58,-2.87,2.29,3.92,7.11,7.67,-2.05,2.03,7.2,-
2.49,5.23,-3.68,3.17,0.7,7.64,-1.82,5.45,-3.76,2.45,1.56;];

[p2,ps]=mapminmax(p);

[t2,ts]=mapminmax(t);

rand('seed',931316785)

[trainV,val,test]=dividevec(p2,t2,0.20,0.20);

net=newff(minmax(p2),[18 1]);

[net,tr]=train(net,trainV.P,trainV.T,[],[],val,test);

a2=sim(net,p2);

a=mapminmax('reverse',a2,ts);

[m,b,r]=postreg(a,t);

a2=sim(net,test.P);

a=mapminmax('reverse',a2,ts)

newp=mapminmax('reverse',test.P,ps)
```

# APPENDIX 6.1

# RESULTS – IMAGE PROCESSING

| | **Automated (No. of snarl turns/25cm)** | | | | **Manual (No. of snarl turns/25cm)** | | | |
|---|---|---|---|---|---|---|---|---|
| Sample No. | **84 tex (7Ne)** | **59 tex (10Ne)** | **37 tex (16Ne)** | **29.5 tex (20Ne)** | **84 tex (7Ne)** | **59 tex (10Ne)** | **37 tex (16Ne)** | **29.5 tex (20Ne)** |
| 1 | 20 | 28 | 22 | 28 | 20 | 28 | 24 | 26 |
| 2 | 25 | 23 | 25 | 25 | 24 | 27 | 24 | 22 |
| 3 | 21 | 26 | 20 | 28 | 21 | 27 | 22 | 24 |
| 4 | 20 | 22 | 19 | 28 | 22 | 23 | 25 | 27 |
| 5 | 19 | 24 | 23 | 27 | 18 | 27 | 24 | 27 |
| 6 | 21 | 24 | 21 | 22 | 21 | 25 | 23 | 24 |
| 7 | 17 | 26 | 22 | 26 | 18 | 25 | 23 | 26 |
| 8 | 22 | 22 | 22 | 32 | 22 | 23 | 25 | 24 |
| 9 | 20 | 27 | 16 | 29 | 19 | 26 | 21 | 25 |
| 10 | 19 | 28 | 22 | 21 | 21 | 27 | 24 | 21 |
| 11 | 22 | 24 | 21 | 24 | 18 | 26 | 20 | 25 |
| 12 | 20 | 26 | 25 | 24 | 21 | 25 | 26 | 23 |
| 13 | 19 | 27 | 20 | 28 | 19 | 27 | 19 | 24 |
| 14 | 21 | 25 | 23 | 20 | 21 | 25 | 25 | 25 |
| 15 | 21 | 26 | 18 | 29 | 20 | 28 | 22 | 28 |
| 16 | 22 | 22 | 19 | 25 | 21 | 26 | 26 | 24 |
| 17 | 18 | 28 | 21 | 24 | 19 | 26 | 23 | 28 |
| 18 | 22 | 28 | 22 | 24 | 20 | 29 | 25 | 26 |
| 19 | 22 | 22 | 22 | 24 | 20 | 25 | 24 | 23 |
| 20 | 24 | 23 | 22 | 22 | 23 | 25 | 22 | 25 |
| 21 | 18 | 21 | 22 | 26 | 17 | 27 | 20 | 26 |
| 22 | 16 | 26 | 27 | 22 | 20 | 26 | 25 | 27 |
| 23 | 18 | 22 | 21 | 23 | 20 | 24 | 22 | 24 |
| 24 | 20 | 24 | 23 | 19 | 21 | 25 | 22 | 22 |
| 25 | 18 | 24 | 18 | 20 | 17 | 28 | 21 | 28 |
| 26 | 21 | 25 | 25 | 28 | 22 | 26 | 25 | 27 |
| 27 | 20 | 24 | 19 | 27 | 19 | 26 | 17 | 24 |
| 28 | 24 | 22 | 23 | 24 | 20 | 25 | 24 | 25 |
| 29 | 21 | 25 | 23 | 32 | 19 | 28 | 23 | 28 |
| 30 | 23 | 24 | 22 | 26 | 20 | 26 | 25 | 28 |
| 31 | 17 | 23 | 21 | 21 | 17 | 25 | 23 | 24 |
| 32 | 22 | 25 | 24 | 26 | 21 | 24 | 26 | 24 |
| 33 | 18 | 27 | 23 | 24 | 19 | 21 | 23 | 25 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 34 | 20 | 26 | 19 | 23 | 18 | 28 | 22 | 25 |
| 35 | 20 | 25 | 23 | 23 | 19 | 26 | 24 | 21 |
| 36 | 22 | 30 | 23 | 26 | 23 | 27 | 23 | 25 |
| 37 | 20 | 25 | 24 | 29 | 20 | 27 | 25 | 25 |
| 38 | 19 | 28 | 20 | 31 | 19 | 26 | 21 | 24 |
| 39 | 21 | 28 | 21 | 26 | 22 | 27 | 24 | 24 |
| 40 | 20 | 29 | 22 | 19 | 20 | 26 | 21 | 22 |
| 41 | 21 | 24 | 24 | 24 | 19 | 24 | 21 | 23 |
| 42 | 18 | 26 | 19 | 20 | 18 | 25 | 22 | 22 |
| 43 | 22 | 25 | 21 | 23 | 20 | 27 | 23 | 26 |
| 44 | 19 | 25 | 19 | 24 | 20 | 27 | 20 | 23 |
| 45 | 20 | 25 | 25 | 24 | 19 | 24 | 27 | 22 |
| 46 | 19 | 25 | 19 | 29 | 19 | 25 | 20 | 26 |
| 47 | 22 | 27 | 21 | 27 | 20 | 27 | 25 | 25 |
| 48 | 24 | 22 | 19 | 19 | 20 | 26 | 23 | 23 |
| 49 | 17 | 18 | 24 | 24 | 19 | 25 | 23 | 25 |
| 50 | 19 | 18 | 18 | 24 | 16 | 26 | 23 | 21 |