CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is concerned with the literature review on weft-knitted fabrics with reference to some selected areas. Since a voluminous amount of literature is available, this review will be somewhat biased towards certain topics. A considerable amount of work has been carried out on spirality, physical and mechanical properties, and chemical finishing of knitted fabrics. This survey is based upon an intensive search of the journals published in textile technology. Articles from other sources are also included, and the subject is reviewed under different captions.

The concern of the previous workers with the above aspects namely, spirality, physical properties of weft-knitted fabrics, handle and mechanical properties is reflected in the following literature review.

2.2 SPIRALITY

2.2.1 The Nature of Spirality (De Araujo and Smith 1989)

In many tension-free, tubular single yarn fabrics, knitted in a plain stitch on a circular one needle system knitting machine, the lengthwise rows of loops (stitches) called needle lines or wales, should normally occupy a truly vertical line, parallel to the edges of the fabric and at right angles (90°) to the crosswise rows of loops called courses, when the fabric is undistorted. In practice, however an undesirable phenomenon becomes vividly apparent, where the wales show a pronounced bias towards
the left or the right. This fault occurs particularly in single jersey knitted fabrics and garments which have a dissymmetry of the loop between the face and back of the fabric. This results in seams which do not run parallel to the edges of garment made up from such material, although the line of courses remains perpendicular to the edges of the fabric. This defect has been appropriately termed by Davis, Edwards and Stanbury (1934) as spirality since it occurs chiefly in tubular fabrics where the wales follow a spiral path around the axis of the fabric, forming an angle with the perpendicular. This angle is termed as the "spirality angle", and is a measure of the fabric spirality.

If the loops of each course, on the technical face of the fabric which has been produced on a knitting machine are examined closely, an inclination to lean slightly to the right (or left) is observed, indicating an excess of yarn on the left or right hand side respectively of the loop, i.e., the formation of each loop is just a little lop sided. The lifting of the one side of the knitted loop from plane of the fabric is the cause of the appearance of an almost rib-like structure form, as the wales are bunched together (Nutting, 1960).

When the fabric is on a knitting machine, the magnitude of this distortion is unpredictable because of the imposition of strains on it due to the take-down tension (Charnock, 1977). As the fabric is released from the stress due to this tension, a complete change occurs in the shape of each of its unit cell (loops). This rearrangement of the fabric structure results in an initial fabric distortion. If the fabric undergoes a process of wetting (immersing in water, dyeing, washing), there is a further distortion of the fabric which is mainly a result of reappearance of the forces in the yarn which have been "relaxed" in the earlier steam setting of yarn (Fletcher and Roberts, 1953). This factor must be recognised in producing a commercially acceptable washable product (Knapton et al. 1971).
Many workers (Lord et al. 1974, Buhler, 1986) who dealt with this phenomenon of spirality agree that the main reason for this defect "is the unbalanced torque within the yarn, shown by its twist - liveliness, the release of torsional potential energy in the yarn" rather than just the presence of the twist alone. In combination with the unbalanced active torque in the yarn, there is the contribution of fabric geometry. The degree of freedom of yarn movement in the fabric structure contributes significantly to the rise of spirality (Nutting, 1960). The more slack the fabric structure, the greater the spirality. This slackness can be achieved by two ways; by changing the tightness factor or, by changing the linear density of the yarn. It has been stated that the loop twisting over to approximately the same angle as the spirality angle, is the result of the section of yarn in each loop that is trying to move to "a state of lower strain under the constraint of forces from neighbouring loops" (Haigh, 1987). It has been shown by Leaf and Glaskin (1955) that much of this distortion arises from the residual torque in the yarn. Newly produced ring spun yarns exhibit a tremendous tendency to untwist, before being treated with any dry or wet relaxation method. This phenomenon could be explained by taking into consideration that elastic stresses as well as torsional forces (torque) set up in the component fibres by the twisting action during the spinning process, attempt to be relieved. This tends to cause an opening up of the yarn and gives rise to yarn and fabric defects (e.g., snarls, spirality, cockling). Hence, "the greater the twist liveliness, the greater the spirality" (Nutting, 1960). At this point, it is necessary to mention that, although this statement is generally acceptable, it was found in the literature that there is a confusion between the twist amount in the yarn and the yarn torque. Some statements which reflect this, are given below: "the degree of spirality is related to the twist factor (number of turns per length of the yarn)" (Brackenbury, 1992) yarns with lower turns per unit length, tend to develop less spirality in the fabrics than yarns with high twist levels ... "spirality increases with the turns per inch ...", "spirality is often due to an excess amount of twist in the yarn from which the fabric is knitted ...". 
2.2.2 Direction of Spirality

It is well known that the direction of the spirality in fabrics knitted from singles short staple yarns is normally determined by the direction of the yarn twist (De Araujo and Smith 1989a). If a Z-twisted yarn is used for the production of a knitted fabric, the technical face of the fabric exhibits spirality in the Z direction and vice versa (Fig.2.1a and 2.1b).

2.2.3 Measurement of Spirality

Several standards are available for determining the spirality of knitted fabrics, e.g., ASTM D3882-88-1997. British standard 2819 (1990), IWS test method No.276.

The angle of spirality can be measured with the help of a protractor or by using a specially designed transparent plastic board as is shown in Fig.2.2. The line EF, which is perpendicular to the sides AB and CD of the rectangle ABCD plays the role of the reference line of a wale in the ideal perpendicular relation that exists between wales and courses in an undistorted knitted fabric. If the line AB tallies with a course and the line EG lies along the actual line of the wales, then the angle FEG is the angle of spirality. Using the distances AD = 10 cm and FG (h cm), Oinuma and Takeda (1988) calculated the "percentage spirality" (PS %) which is expressed by the following equation: \( PSD(\%) = \left(\frac{h}{10}\right) \times 100 \), and it is considered as the sum of the "net" spirality caused by the yarn torque and the "additional" spirality caused by all other factors.

Another test method for measuring the spirality of knitted fabrics has been proposed by AATCC (1995). In this test, the fabrics samples are marked with a square before washing and drying Fig.2.3. The changes in the diagonals of the square measured to calculate the percentage spirality (PS) given by the following formula:
Direction of Spirality (Wale skew).

Z Spirality

S Spirality

Figure 2.1a    Direction of Spirality (Wale skew).
Figure 2.1b  Fabric distortion due to spirality.
Figure 2.2 Transparent board having a protractor configuration on it.

Figure 2.3 Method for the calculation of the percentage spirality by AATCC
Another test for measuring spirality involves use of "open pillowcase" construction which enables seam overlap to be measured, and hence the angle of spirality to be determined (Anand, 2000).

2.2.4 "Acceptable" Spirality

Over many years in dealing with spirality, many workers, researchers and manufacturers have set limits of spirality acceptability. For some, the maximum spirality angle of 5° is acceptable whereas for some others the angle of 7° is taken as the upper limit. It is also found that some exporters stipulate 3° for accepting the knitted fabrics. In U.S.A., a percentage spirality of 8° is considered as the maximum a fabric may exhibit to be acceptable by the making-up industry.

2.2.5 Effect of Knitting Machine Factors on Fabric Distortions

A point worthy of consideration is the effect of the knitting action on fabric distortions.

First, a distinction between the "spirality" and the "drop" or "corkscrew" phenomena should be made to avoid any possible confusion.

"If the wales are skewed from the vertical, the resulting configuration is called a "wale skew". If the courses are skewed from the horizontal, the resulting configuration will be called "course skew" (Fig.2.4).

"Wale skew" widely accepted as the well-known term "spirality", is due to the twist liveliness (Buhler and Haussler, 1985). "Course skew" has been described as the "drop" effect (Oinuma and Takeda, 1988), and is
Figure 2.4 Comparison between Drop and Spirality Effects.
inherent in the process. This occurs due to the helical disposition of the courses, and depends on the fact that articles produced with a spiral configuration have a "start" and an "end" of a coil not on the same plane.

In weft circular knitting machines, fabrics present a course skew because the yarn is knitted in the circumferential direction. The degree of the course skew or drop depends on the number of feeders used on the knitting machine (de Araujo and Smith, 1989a). It is true that, in recent years, the machine manufacturers tend to increase the number of feeders. For this reason, the problem is likely to become more acute. The degree of drop is a function of the step S of the helix due to the number of courses per centimetre and the machine circumference. The direction of the inclination of the drop depends on the direction of either the revolving cam box or the rotating cylinder (Fig.2.6).

In some papers there is a suggestion that both the spirality and drop effect contribute to the final distortion or "total" spirality. It becomes essential, therefore to describe the effect of the number of feeders on the drop phenomenon as well as to investigate the contribution of the drop to the "total" spirality of the produced fabrics.

Araujo and Smith (1989ab) have attempted to explain their statement of "total" spirality by, carrying out the following analysis.

Fig.2.5 represents the development of spirality in a single jersey fabric knitted with a Z-twisted yarn on a multifeed circular machine with an anticlockwise rotating cylinder.

Referring to Fig.2.6.

\[
\begin{align*}
XX' & = \text{Position of a course due to the total spirality} = \frac{N}{W} (\text{Open width of fabric}) \\
AA' & = \text{Position of a wale due to the total spirality}.
\end{align*}
\]
Figure 2.5 Effect of the number of feeders on the fabric drop (Course skew).
BB' = Position of a wale when spirality (drop) due to the number of feeders exists.

XD = Position of a course when spirality (drop) due to the number of feeders exists.

XD = Displacement between two consecutive courses knitted by the same feeder = F/C

F = Total number of feeders on the knitting machine.

N = Total number of needles in the knitting machine.

C = Number of courses per unit length.

W = Number of wales per unit length.

α_f = Spirality (drop) angle due to the number of feeders (Y^Ô B)

α_y = Spirality angle due to the yarn twist liveliness (BÔ A)

α_ty = "total" spirality angle (Y^Ô A or A^Ô Y')

From the triangle DXX':

\[
\tan \alpha_f = \frac{F/C}{N/W} = \frac{F}{N} \times \frac{W}{C}
\]  \hspace{1cm} (2.2)

Considering that

\[
W = \frac{K_w}{1}; \quad C = \frac{K_c}{1}
\]  \hspace{1cm} (2.3)

and loop shape factor

\[
K_{c/w} = \frac{K_c}{K_w}
\]  \hspace{1cm} (2.4)
where $K_{\alpha}, K_{\gamma}$ are non dimensional parameters whose values depend on the state of relaxation and $l$ is the loop length (mm), then

$$\tan \alpha_f = \frac{F}{N} \times \frac{1}{K_{\gamma\omega}} \Rightarrow \alpha_f$$

$$\alpha_f = \tan^{-1} \left( \frac{F}{N \times K_{\gamma\omega}} \right) \quad (2.5)$$

"This last equation shows that the angle of the course skew (drop) depends not only on the number of feeders but also on the shape of the loop in the particular state of relaxation and on the number of active needles in the knitting machine, which in turn depends on the machine cut and diameter (de Araujo and Smith, 1989a,b).

If the direction of the rotating cylinder reverses (i.e., clockwise) then Fig.2.6 will change to the form shown in Fig.2.7 indicating that the overall spirality angle will be reduced.

It could be concluded then, that in many cases it would be beneficial rather than detrimental from the "total" spirality point of view, to use a larger number of feeders on a machine, as the drop (due to the number of feeders) and the spirality (due to the yarn twist liveliness) "can combine together to create more skew, or they may partially offset each other and result in less skew". On the other hand, multiple feeders increase the chance of a stripy fabric being produced because of possible yarn linear density and/or shade variation between feeders (Walker and Sleath, 1950).

Further to the conclusions of the above investigation, it has been suggested that the number of feeders is responsible only for a distorted appearance of the fabric (in terms of drop effect), while the actual spirality is the same whether a single or multifeed machine is used (Fig.2.8.).
Figure 2.6 Development of spirality in a single jersey fabric knitted from a Z-twisted yarn on a multifeed circular machine with an anticlockwise rotating cylinder.

Figure 2.7 Development of spirality in a single jersey fabric knitted from a Z-twisted yarn on a multifeed circular machine with a clockwise rotating cylinder.
Figure 2.8 Appearance of distorted fabric due to the drop effect (a) one feeder (b) five feeders with $0^\circ$ spirality angle.
2.2.6 The Effect of the Rotation and its Direction of the Cylinder and Cam Box on Spirality

In the knitting industry, two types of circular single bed machines are, in terms of their rotating parts, responsible for the knitting action: machines with revolving "cylinder cam system" (cam box) and machines with rotating "cylinder needle housing" (cylinder). These parts can be rotated clockwise or anticlockwise. Thus, when a knitting machine has a clockwise revolving cam box, the stationary cylinder is rotating relatively anticlockwise, and when a machine has a clockwise rotating cylinder, the stationary cam box is relatively revolving anticlockwise and vice versa. It has been stated that the direction of rotation of these knitting parts influences the positioning of the loops (stitches). Experiments were, therefore, carried out to determine the actual effect of the direction of rotation on the spirality of tubular single jersey knitted fabrics (Buhler, 1985). In these experiments, a twist-free (neutral) polyester monofilament was knitted on a machine having an anticlockwise rotating cylinder. On a close examination on the fabric produced, a slight tendency of the loops to follow the running direction of the cylinder could be detected i.e., the individual loops were found to be inclined to the right. The loop shanks on the right were also shorter than those on the left. It has been argued that this was a result of the tension imbalance between the two "legs" of the loop during the stitch formation (de Araujo and Smith, 1989ab), and this "skewness is, especially noticeable with monofilament yarn because of its high bending rigidity. "The inclination of the stitches against the direction of knitting can be traced back to the fact that the following stitch shank running in the direction of the thread-feed is subjected to higher levels of tension during interlacing process of the stitches" (Buhler and Haussler, 1986).
Disagreements concerning the actual influence of the rotation of particular mechanical parts of the knitting machine exist between various workers.

It would appear advantageous in terms of spirality reduction, to work with Z-twisted yams on knitting machines with clockwise rotating cylinders. On the other hand, others are of the opinion that the total spirality is reduced when Z twisted yams are knitted on a machine with an anticlockwise rotating cylinder. There are also some workers who make no stand, since their experiments showed opposing results. Still other researchers consider, the effect of this factor as negligible (Davis, Edwards and Stanbury, 1934). The results are summarised and presented in Table 2.1.

Table 2.1 Effect of the direction of the cylinder rotation on spirality

<table>
<thead>
<tr>
<th>Direction of the Additional spirality</th>
<th>Direction of cylinder</th>
</tr>
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<tbody>
<tr>
<td>Z</td>
<td>Anticlockwise</td>
</tr>
<tr>
<td>Z</td>
<td>Anticlockwise</td>
</tr>
<tr>
<td>Z</td>
<td>Anticlockwise</td>
</tr>
<tr>
<td>Z</td>
<td>Clockwise</td>
</tr>
<tr>
<td>Z</td>
<td>Clockwise</td>
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<td>Z</td>
<td>Clockwise</td>
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<td>Z</td>
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This skew effect, due to the direction of the rotation of the knitting machine, is negligible when compared with the possible yarn effects on the spirality angle and can be disregarded. But, even if invisible, it contributes slightly to an increase or decrease of the spirality angle. This factor related to the spirality should be taken into account when seeking the explanation of relative defects.
2.2.7 The Effect of the Knitting Speed on Spirality

It could be said that there is no clear picture about how and whether the variation of knitting speed, when comparison is made between machines with the same settings, processing the same yarns, affects the fabric distortion (skewness - spirality). This speed is interwoven with other factors, like, for example, the direction of the motion of elements (cylinder cam box) cam setting, the yarn input tension and yarn lubrication.

From an experiment carried out to investigate the possible effect of speed, it was observed that under high speed conditions (280 revolutions per minute) the resultant fabric appeared to be slightly distorted in terms of spirality (4°). When normal speed (80 revolutions per minute) was used, no spirality could be observed. The conclusion was that "if the speed of the machine had any effect on spirality, it was not a factor of any great importance".

Other workers attempted to relate the effect of the knitting speed on spirality with alterations in the loop length (Peat and Spicer, 1973; Banerjee and Alaiban, 1987). They concluded that there was no correlation. Furthermore, there is an opinion that the velocity affects the lopsidedness of the loops in the case of oscillating motion of the cylinder producing an "additional spirality" due to the high velocity. Also, it has been argued that this speed causes changes in the additional spirality that is in inverse proportion to the loop length, but not in the spirality due to the residual torque in the yarn (Oinuma and Takeda, 1988). These changes of the additional spirality were attributed to "needle fling" changes in needle direction due to the inertia force on the needle after the knitting point.

It was concluded that, since there is no clear evidence of the possible effect of the knitting speed itself on the spirality, it can be neglected.
2.2.8 The Effect of the Take-down Tension on Spirality

One of the factors contributing to a successfully completed knitting cycle is the tension applied to the previously formed loop on the needle (or macroscopically, to the entire knitted fabric), in order to ensure reliable clearing of the knitted loops from the needles. It is reported (Kurbak, 1982), that there are three main objectives for the existence of this "take-down" tension.

1. To keep the loop hard against the needle in order to operate the latch to close or to open. Tension is necessary to overcome the flexural rigidity of the yarn that would otherwise move the yarn away from the needles.
2. To prevent the loop and the fabric from moving up and down, as the needle moves up and down. Here, tension is necessary to overcome the frictional force between the needle and the loop.
3. To draw the loops that have just been knocked over the needles.

All power-operated circular weft knitting machines are fitted with an adjustable fabric tension arrangement, allowing the take-down tension to be varied, in order to hold the fabric in position during knitting and advance it at the rate it is produced. Usually, this mechanism consists of two to four take-down nip rollers positioned horizontally one next to the other ensuring the avoidance of any fabric slippage. The fabric as it comes out of this rollers system is wound firmly on the take-up cylinder and is termed as a "batch".

It has long been recognised that, by altering the take-down tension, the dimensions of a fabric on a knitting machine can be materially affected. In the case of increasing tension, a marginal increase in loop length occurs.
resulting in a stretcher-lengthened fabric with the consequent decrease in its width. The fabric weight per unit length decreases as the fabric has a lower value of courses per unit length. The main defect that commonly appears in the fabrics is due to the unevenly distributed take-down motion and is termed "bow". Although this distortion seems to be permanent, as long the fabric remains in the dry state condition, being stretched or not, wound on the take-up cylinder (batch) giving the impression that a "real change in fabric dimensions has been produced by this adjustment", the change in take-down tension does not alter the yarn length used for the formation of a loop so that no permanent alteration to the knitting quality or fabric dimensions has been made. Oinuma and Takeda (1988) have indicated that "input tension and take-down weight affect the loop length". It could be stated that this occurs in cases where there is excessive take-down tension applied to the fabric in the presence of a non positive yarn feeding system. It has also been mentioned, without any experimental confirmation, that an excessive take-down tension influences the take-up of yarn at the feeders in the case of flat V-bed knitting machines.

Some other defects associated with high take-down tension are: "a greater incidence of cuts and holes in the fabric as well as wear on the knitting elements and problems when knitting weak yarns" (Spencer, 1986).

Considering these statements, it is essential to knit with low yarn input tension and low fabric take-down tension, thereby preventing the tensile failure of the yarns.

A factor which has to be taken into account is the fact that there is no widely accepted method for measuring the take-down tension. In practice, due to the lack of calibrated take-down mechanisms, the appropriate setting of this tension relies on experience. Therefore, it is doubtful how "the distortion of the fabric on the machine due to take-down tension could be predictable" (Hepworth, 1982).
It is noticeable that after knitting and during a "dry relaxation" or a "wet relaxation" period, the fabrics, being relieved from strains, (mainly due to the take-down tension) imposed on them, tend to be configured to what it is called dry or wet "relaxed physical form". This statement can be tested by comparing the numbers of courses and wales per unit length and width, measured before and after the relaxation.

Recent work carried out by Hepworth (1993), investigating this effect by using a theoretical model, showed that there was a range wherein the angle of spirality increases with the take-down tension. In the knitted structure, the contact points between yarn loops are at considerable pressure which results in jamming. It is only when the fabric tension has reduced that pressure, that the spirality begins to decrease as the courses start to become separate. The conclusion was that the relaxed fabrics showed higher spirality when subjected to take-down tension.

2.2.9 The Effect of the Cam box Setting (Tightness factor) and Machine Gauge on Spirality

An investigation of the relationships of the course and wale spacing before and after laundering in the case of relaxed fabrics showed a linear relation, indicating that the changes of the loop shape are similar in both tightly and loosely knit materials (Fletcher and Roberts, 1953). On the contrary, some workers disagree with this statement, indicating that "the spirality" of the loops is much greater when the fabric is slack" (Banerjee and Alaiban, 1988) or, the tighter the knitted structure, the less distortion develops. This is attributed to the jamming that tends to occur with tight stitches; "the tighter the stitch, the less the neighbouring yarns in the loop can move relative to each other".

Another point worthy of mention concerns the stitch length and the yarn count; "A fabric produced with a shorter stitch length or relative
tightness at which a fabric is knitted, for a given yarn count will develop less spirality when compared to a fabric produced from the same yarn at a longer stitch length”.

In terms of machine gauge, there are conflicting opinions. On the one hand it has been stated that the spirality increases with the coarseness of the gauge (Banerjee and Alaan, 1988). On the other hand it is claimed that “the spirality of a fabric increases, with the fineness of the machine gauge, for a constant angle of yarn twist. The rate of increase appears to vary with the type of machine used”.

2.2.10 Existing Methods for the Reduction of Spirality

“Spirality, although as old as the hills, is regarded as a mysterious disease, and as such requires mysterious cures. The facts of the problem are delightfully simple, the difficulty usually arises when a practical cure is being sought”.

Theoretically the effect of spirality must exist, potentially at least, with all single yarns, except in the case of twistless yarns (King, 1934).

Various methods have been adopted for overcoming this defect; these are now described.

2.2.11 Mechanical Methods
2.2.11.1 Use of folded yarns

Many workers (De Araujo and Smith, 1989a; Charnock, 1977) have opined that the most suitable method for producing spirality-free knitted fabrics is by using two-folded yarns. These yarns are called “dead”, a term used in the industry, as they are left with a reduced or null residual torque or twist liveliness. This is because the twisting together of two ends of yarn,
having the same twist direction, in the opposite direction to the spinning twist, exerts a balancing and stabilising effect. The opposing torsional forces in the singles yarns and the resulted folded yarn are counterbalanced. Because of problems in dealing with the appropriate relation between the two amounts of twist, any small amount of spirality which may develop will be in the direction of the residual twist.

Replacing singles yarn by folded yarn gives rise to an improved fabric appearance; a smoother touch even light reflection, better stretch and more vigorous recovery in the resultant fabric. Also, folded yarns are more resistant than a singles yarn to the effects of distortion and other physical effects and can be made even more stable if the yarn package is dyed in this form. On the other hand, the use of two folded yarns in knitting single jersey fabrics has the disadvantages of high yarn material and yarn production costs. Garments (e.g., T-shirts) knitted from such yarns are heavier, which is often an undesirable factor. For a given end product, the singles yarn used for the production of the two-folded yarns must be finer resulting in a dramatic increase of the production costs.

2.2.11.2 S-twisted and Z-twisted single yarns in the same feeder

When using two ends of yarns, having equal twist amounts and in particular equivalent twist liveliness but opposite twist directions (S,Z) in the same feeder, the tendency to distort the formed knitted loops - towards the one or the other direction (S,Z) are neutralised. Therefore, the produced fabric appears to be straight.

In practice, it is difficult to produce yarns with exactly similar twist liveliness, and fabrics produced by this method show a small degree of spirality. In fact, it has been suggested that the degree of spirality angle, "corresponds approximately and is smaller than the anyone of them individually. In addition the spirality of this resultant fabric assumes the
twist direction of the yarn with higher twist level or twist liveliness. It may be said that this method, similar to what is termed "plaiting", is an effective technique for keeping the spirality of the produced fabrics to a maximum.

2.2.11.3 S-Z-Twisted singles yarn in alternate feeders

As stated earlier, Z-twisted yarns produce, Z spirality, and S-twisted yarns with equivalent twist levels will produce an overall "spirality free" fabric. Unfortunately this method, although reduces spirality results in a fabric which has an irregular and uneven appearance, and presents a "cockling" effect on the fabric surface. The reason for this appearance can be identified by closely examining the wale loops. Loops in each course are distorted in opposite directions, following the direction of yarn twist producing a "herring-bone" effect.

Although this method is not suitable for the production of cotton or wool plain jersey knitted fabrics, it is commonly used in the manufacturing of stretch stockings made from fine nylon yarns. The "herring-bone" effect, which is not objectionable in the latter case, gives the fabric a greater potential for lengthwise stretch.

In both methods presented in the previous sections the replacement of the yarn packages can reduce the fabric quality and lead to problems, as both these techniques are labour intensive. They include yarn package marking and inspection for the avoidance of mixing the yarn, types during the fabric production.

Recently a "Z technology" introduced by Monarch to knitting machines appears to be less prone to spirality. No information regarding this technology is yet available. It is probable that a new type of sinker movement induces less torque in knitting with latch needles.
2.2.12 Chemical Methods

Although fabrics produced from mainly from cotton yarns are the object of this work, it may be of interest to note that probably, the first attempt for chemical correction of the detrimental effect of spirality was made on fabrics produced from crossbred worsted yarns. King (1934) has reported that spirality in such cloths disappeared under a "cold crabbing" a process using cold sodium sulphide solutions. In explaining the mechanism of this process, he concluded that "it is the cross linkage (disulphide linking) which is mainly concerned in the spirality removal". However, the use of sodium sulphide caused decomposition of the wool fibres resulting in the weakening of the fabric.

2.2.12.1 Mercerisation of cotton yarns

Experiments carried out by Banerjee and Alaiban (1988) showed that there was a 10-13% reduction in spirality in dry relaxed fabrics produced from mercerised cotton yarns. In terms of twist liveliness the mercerised yarn exhibited a drop of about 45%. Cotton yarns, which were not mercerised, were also made into fabrics. The reduction in spirality obtained by mercerising in the fabric state was 20-30%. They reported that "fabric mercerisation causes a large reduction in loop asymmetry than yarn mercerisation, though the treatment remains the same". Keeping in mind that mercerisation is a wet relaxation process accompanied by fibre and yarn swelling and resulting in appreciable mobility, it would appear that the movement of macro-elements constituting a fibre, plays a decisive role in the relaxation process. Their conclusion is an agreement with that of previous workers and states that although mercerisation is an efficient wet relaxation process giving the best results compared to others, it is not a complete solution, as the spirality of single knitted fabrics is concerned.
2.2.12.2 Use of small percentage of low melt polyester fibres

In this method, a small percentage of low melt polyester fibres is blended with cotton. The resulting yarn is heat treated. This process melts the polyester preventing the cotton fibres movement and reduces spirality (De Araujo and Smith, 1989a).

This method does not completely eliminate spirality, and it is possible that the resulting texture is not pleasant to the wearer as the yarn and fabric become rather stiff.

2.2.12.3 Application of resins (Brackenbury, 1992)

Resin treatments, known as cross linking are used sometimes for reduction of the spirality. The resin is applied to the fabric in aqueous solution and is set by passing the fabric through a high temperature stenter. Besides spirality reduction, the process improves dimensional stability, appearance and handle. The main drawback is the weakening of the cotton fabric.

2.2.12.4 Finishing methods

For the minimisation of the various defects such as yarn snarliness spirality and cockling that arise from the yarn "twist liveliness", the twist setting i.e., the process of relieving the stresses set up in textile fibres by twisting or relaxation process may be applied. The main requirement for this process is the action of heat in the presence of moisture on the yarn. As many workers have mentioned, twist setting results in an improvement of the mechanical stability of yarns. This process ensures that even highly twisted yarns become "dead" whilst retaining their twist level.
2.2.12.5 Yarn setting

A number of yarn setting methods has appeared in the textile industry that have as a common characteristic, the setting of atmospheric conditions of high temperature and high humidity.

A method, used in the past showing good results in terms of twist relaxation was the "yarn storage" method (Buhler and Haussler, 1986). Single yarn twists more easily when it has had a resting period of time, allowing any static to disperse and giving the yarn a chance to pick up some of the moisture content lost during drawing and spinning. Storing the yarn packages for a proper period of time at adequately high temperature and relative humidity (70-75%) contributed to a twist relaxation. However, it is necessary to exercise care to protect the yarns from condensed water, since "water condensing on walls, ceilings on pipes must be prevented from dropping on the yarn and causing subsequent stains, spots and imperfections in the goods". This technique could not be recommended for today's industrial conditions, where a speedy flow of all material throughout the mills is of paramount importance.

A more effective method of twist setting is accomplished by subjecting the yarn to a hot and humid conditions for a period of time, sufficient enough to bring out the "deadness" required depending upon the level of yarn liveliness. More severe setting will be required when the degree of the yarn twist is greater. For this method, yarn package form is placed in a perfectly enclosed chamber and regulated humid air (heated air and moisture) is forced into the chamber for a given period of time. It should be clearly understood that highly twisted yarns must be set under tension in order to avoid the permanent fixation of the snarls which can occur when the yarn is in the hank form.
2.2.13 Knitted Fabric Setting (Hurt, 1966; Suh, 1967)

In knitted structures such as single jersey tubular fabrics, the spirality may be temporarily corrected when it is not too severe. This can be achieved by low levels of fabric strain, achieved by using a former steam processing or steam pressing. For worsted fabrics, high temperature steaming of the fabric reduces spirality often after scouring but not after dyeing. It should be emphasized here that boarding or calendaring of the fabric under ordinary finishing conditions are only transient methods because as soon as the fabric is wet again, during subsequent washing or scouring, it regains its spirality resulting in a consequent loss in appearance and discomfort in wear. In many cases, the fabric returns to the distorted shape it might have had, if it was produced from the same unset yarns: "As the fabric dries out, the configuration of the yarn in loops tends to remain unchanged from that assumed in the wet state. Thus the fabric is in a "set" condition retaining very little of the internal stresses which previously existed. The phenomenon is best observed by comparing two yarns from fabrics taken before and after washing. If this is done, it will be found that the dry, unwashed sample tends to return its original straight configuration. But the sample of yarn from a washed sample, which has been allowed to dry in the knitted state will, upon unravelling, tend to remain in the configuration of the loop. Thus, it is not surprising that the washed and shrunk fabric will not return to its original shape after drying but retains the new dimensions resulted from wetting.

One drawback of both steam and water setting processes is the drying stage which is time and energy consuming. Nowadays, the use of expensive radio frequency dryers has reduced the actual time of drying but little work has been done concerning the effect of the use of such equipment on the yarns and fabrics.
However it should be pointed out that neither steam nor water set processes prevent the spirality of the knitted structure entirely. They merely reduce its level.

From an extended survey of the textile literature, it is evident that much research has been carried out investigating the dimensional stability of knitted fabrics. A significant amount of this work includes the development of theoretical models of the knitted structures. Most of the theoretical models were derived in order to explain fundamentally the experimental findings of other workers. A brief description of the various theoretical models that attempt to relate the structure of a plain knitted fabric with the properties of the constituent yarn is presented.

2.3 RELAXATION OF KNITTED FABRICS

The application of forces and the generation of couples on a straight unstrained rod may result in the formation of a two dimensional loop. During straining, if only bending takes place, the loop formed is perfectly symmetrical about the central axis. If torque is applied to the rod prior to bending, the loop shape is no longer two-dimensional. In practice, after knitting, the loop shaped yarn desires to return to its straight state but this is prevented by an equal and opposite reaction from the interlocking yarns. It was Doyle (1953) who first suggested that, in the absence of external forces on the fabric, or internal factors such as friction between yarns, each loop in a course would attempt to come to rest in the shape in which the strain energy is a minimum. Furthermore, Doyle (1953) put forward the hypothesis, that the number of stitches per fabric area depends only on the stitch length l.
2.4 RELAXED FABRIC DIMENSIONS

Munden (1959) reported that the fabric dimensions are completely determined by the knitted loop length and introduced the following relations that were found to apply to relaxed knitted fabrics.

\[
C = \frac{K_c}{1}, \quad w = \frac{K_w}{1}, \quad S = C \times W = \frac{K_s}{1^2} \tag{2.6}
\]

where

- \( C \) is the number of courses per unit length.
- \( W \) is the number of wales per unit length.
- \( S \) is the stitch density (number of loops per unit area)
- \( l \) is the loop length
- \( K_c, K_w, K_s \) are constants such that \( K_s = K_c \times K_w \)

He also defined two states of relaxation: the dry relaxed state to which unset fabrics would tend, on being left to lie on a flat horizontal surface under no tensions, and the wet relaxed state reached by fabrics that had been wetted in some prescribed way, allowed to dry flat under no tensions and then conditioned in a controlled atmosphere.

A practical approach to the investigation of the relaxed configurations made by many workers raises many problems. Treatments necessary to bring a fabric to a relaxed state are lengthy, and there is also the difficulty of recognising when such a state has been reached. It has been generally concluded that, "the knitted fabrics should be allowed to relax as freely as possible during finishing in order that they should approach as closely as possible their stable shapes and dimensions which are governed by the normal physical principles of minimum energy stored within the fabric structure". Nutting and Leaf (1964) have shown that most probably, the dimensions of the relaxed loop also depend upon the ratio of the bending rigidity to the shear rigidity of the yarn. This fact highlights the basic
inaccuracy of the Munden's model where the three-dimensional nature of the loop has been neglected. For the same reason Postle and Munden (1967a) attempt to produce a force-determined model resulted in inconsistencies.

2.5 GEOMETRICAL MODELS OF THE PLAIN KNITTED STRUCTURE

Chamberlain (1926), Peirce (1947), Leaf and Glaskin (1955) and Leaf (1960) have made attempts to define geometrically the configuration of the unit cell, the loop of a plain knitted fabric.

The earliest models were based on the assumption that the basic structure was such, in which the shape of the loops was a simple arrangement of parts of circles and arcs joined by straight lines. Peirce (1947) also assumed that these loops, in which maximum packing of the yarns had taken place, lay on a cylinder to allow for the three-dimensional properties of the knitted loop.

Leaf (1960) in his model assumed, that the loops consisted of two elasticas joined as mirror images and that these loops lay on a surface whose cross section was a sine function. "Unfortunately, this model of the loop cannot be regarded as indicating the mechanism by which the loops are actually produced. The form of the elastica assumed requires that the cloth has a tension on it and also requires the pressures that must exist at the cross-over points (Postle, Carnaby and de Jong, 1988).

2.6 FORCE DETERMINED MODELS

The attempts for a purely geometrical approach to the structural behaviour of plain-knitted fabrics were not entirely satisfactory. Force determined models analyse the system of inter-yarn forces acting on a loop
and assuming that the yarn behaves like an elastic rod attempt to calculate the loop shape and from that the fabric dimensions. Because the loop is a 3-dimensional structure, the calculation is very complex. The earlier force determined models resorted to simplification in the system of inter-yarn forces which made the solutions invalid. These models include those of Munden's (1960c) and Shanahan and Postle's (1974a). The only two self-consistent models are those of Hepworth's (1971) and Postle and de Jong's (1988). This was because the first problem of interest was focussed on the problem of predicting fabric dimensions and also because the difficulty of solution restricted interest to the simplest fabric structure, plain knitting, in which the loops were assumed to be symmetrical. Later when computers became more powerful and numerical methods more efficient, Hepworth (1993) was able to solve more complex structures e.g., 1 x 1 rib and plain knitting with asymmetrical loop.

2.7 THE THEORY OF BENDING AND TWISTING OF THE RODS APPLIED TO THE IDEALISED YARN

Love (1944) has established a general theory of bending and twisting of thin rods. Hepworth (1971) summarised this theory as it applied, to the "idealised" yarn and derived convenient equations of equilibrium.

An initially straight rod of circular cross-section is considered which is bent and twisted by the action of forces and couples at the ends.

"Let OX, OY, OZ be a system of fixed axes, with OZ parallel to the central axis of the rod in its unstressed state. At a section of the rod through any point, P, on the central axis, moving axes, P_x, P_y, P_z can be set up so that P_x is along the tangent to the central axis at P, in the direction in which the length S, measured along the central axis is increasing; P_y and P_z are along linear elements of the rod which, in its unstrained state, were parallel to fixed axes OX, OY (Fig.2.9).
Figure 2.9

Bent and Twisted rod by the action of forces and couples at the ends.
If the point P and the system of moving axes $P_x, P_y, P_z$ were allowed to move along the strained central axis with unit velocity, the angular velocity with which the moving axes rotated would have components $K_1, K_2, \tau$, about the instantaneous positions of the axes, where $K_1$ and $K_2$ are components of curvature of the central axis and $\tau$ is the twist of the rod about its central axis.

The "ordinary approximate theory of bending used by Love (1944) states that, if the stress couples have components $G_1, G_2, G_3$ about the moving axes, then $G_1 = BK_1$, $G_2 = BK_2$, $G_3 = C\tau$. Where $B$ and $C$ are the flexural and torsional rigidities of the rod.

Basically, these are the equations that link the external forces acting on the rod, while the curvatures and twist on the other side of the equations can be expressed in terms of co-ordinates of the central axis. These coordinates are the rectangular coordinates $(X,Y,Z)$ of the point P, together with the Euler angles ($\theta, \phi, \psi$) which define the inclination of the moving axis $P_x, P_y, P_z$ relative to the fixed axes as shown in Fig.(2.10).

The curvature and twist can be related to the Euler angles by the expressions:

\[
K_1 = -\frac{d\theta}{dS} \sin \phi - \frac{d\psi}{dS} \sin \theta \cos \phi \tag{2.7}
\]

\[
K_2 = -\frac{d\theta}{dS} \cos \phi + \frac{d\psi}{dS} \sin \theta \sin \phi \tag{2.8}
\]

\[
\tau = -\frac{d\phi}{dS} + \frac{d\psi}{dS} \cos \theta \tag{2.9}
\]

where $S$ is the length measured along the central axis of the rod.
Figure 2.10  Euler Angles.
The relationship between $K_1$, $K_2$, $\tau$ and the stress couples $G$, $G_2$, $G_3$ and also the relationships:

\[
\frac{dX}{dS} = \sin \theta \cos \Psi \quad (2.10)
\]

\[
\frac{dY}{dS} = \sin \theta \sin \Psi \quad (2.11)
\]

\[
\frac{dZ}{dS} = \cos \theta \quad (2.12)
\]

provide six simultaneous differential equations which can be integrated numerically to give the coordinates and the Euler angles at any point of the central axis.

Furthermore, it was shown that the loop shape is completely determined by the ratio of yarn diameter ($d$) to loop length ($l$). In order to calculate the shape of the knitted loop, it was divided into sections, each founded by a point of application of a reaction force, and equations of equilibrium were written for each section. The only information supplied to the computer before the calculation was the value of fabric tightness expressed as $d/l$. The results of the calculation gave values, not only for loop shape and fabric dimensions, but also for the magnitudes and directions of inter-yarn forces.

It was also shown by Hepworth (1971) that loop shape varies with the ratio $d/l$. This is in disagreement with Munden's assertion (1959) that fabric dimensions are determined by loop length but it must be pointed out that his fabrics covered a small range of tightness usually found in commercial fabrics. The theoretical calculations also showed that jamming conditions in the relaxed fabric vary with tightness with no jamming for
slack fabrics \((d/l < 0.0313)\) jamming between courses only, for \(0.0313 < d/l > 0.06\) and jamming between both courses and wales for \(d/l > 0.06\).

### 2.8 NEW APPROACH TO A LOOP MODEL

The models developed described in the previous paragraphs were based on the assumption that the knitted loop was symmetrical. Hepworth modified the previous model by taking into account a twisting couple present in the yarn. This twisting couple represented the yarn twist liveliness. It was pointed out that, on introducing this couple, the loop shape became asymmetrical, and that inevitably led to fabric spirality. Calculations of loop shapes for different values of tightness were made, and in agreement with the experimental observations of previous workers, it was shown that spirality increased with yarn twist level and decreased with increasing fabric tightness.

### 2.9 COMPRESSIONAL PROPERTIES

Alimaa et al. (2000a) report on the compressional properties of knitted fabrics produced from cashmere and polyester fibres in terms of fabric structure and yarn compressional property. The relation between the compressibility of knitted fabrics and structural characteristics (loop length, cover factor and fabric weight) has been studied. A linear relation between the compressibility of knitted fabrics and the loop length has been found to exist. A multiple regression analysis to predict the compressibility of knitted fabrics from the constituent yarn compressional property and the loop length, shows that these parameters account for 93% of the compressibility of knitted fabrics. The shape of compressional curves of knitted fabrics are found to depend on loop construction, loop length and constituent yarn property.
2.10 DIMENSIONAL PROPERTIES

Anand et al. (2000) have made a systematic study on the effect of principal variables on the dimensional stability and distortion of cotton knitted fabrics (plain, 1x1 rib and interlock) following repeated launderings. Laundering procedures include water wash with line drying detergent wash with line drying, water wash with tumble drying and detergent wash with tumble drying. The various properties investigated on the cotton knitted fabrics are stitch length, linear density, shape factor, dimensional stability (length), dimensional stability (width), skewness and spirality.

The results obtained have shown that the stitch length and yarn linear density of the fabrics have not altered significantly upon repeated laundering; this confirms that any dimensional changes occurring after the washing and drying treatments must have been caused by changes occurring in loop shape rather than yarn or loop length shrinkage. This conclusion also confirms in their study that the correct conditions appropriate to the cotton fibre type were used during laundering. Loop shape factor values have been found to be very similar to the classical values reported by a number of previous researchers such as Natkanski (1967), Knapton (1971), Postle (1968), Anand et al. (2000) and Smirfitt (1965).

Lengthwise stability results have shown that there is a significant difference between tumble and line drying. Lengthwise stability, and percent skewness have shown bigger differences between the structures. Spirality and skewness have shown the same trend, and plain single-jersey fabrics have been found to be very susceptible to distortions due to spirality. The average angle of spirality obtained was 22.6°, a figure which would automatically fail by any spirality test standard.

It has been concluded that the plain single-jersey requires special attention when laundering. It would appear that because the structure isiso
unbalanced, it would be unwise to launder the fabric under the same conditions as those applied to the 1 x 1 rib and interlock structures. Tumble drying has been found to cause the most dimensional changes upon the fabric due to a combination of constant slow agitation and temperature. This amalgamation forces the structures to take up their minimum energy state causing the most dimensional changes in the loop shape.

It has been pointed, finally, that it would be necessary to investigate the conditions under which single jersey fabrics can be laundered so that the dimensional changes and distortion are kept to a minimum.

Table 2.2 summarises the papers which are concerned with the spirality of single jersey fabrics.

2.11 EFFECT OF CHEMICAL TREATMENTS ON THE PHYSICAL PROPERTIES OF KNITTED COTTON FABRICS

Cotton knitted structures are inherently resilient and air-permeable, and these properties contribute to their comfort, softness, absorption, drapability, and ease of care. Despite these desirable attributes, the lack of dimensional stability is a major problem with knitted goods. Theoretically, knitted loops move towards a three dimensional configuration of minimum energy as the strains caused during production are allowed to be dissipated so that eventually like all mechanical structures, a knitted fabric will reach a stable set of equilibrium with its surroundings and exhibit no further relaxation shrinkage.

Unfortunately, there are a number of states which may be achieved by different relaxation conditions, such as dry relaxation steaming, static soaking, washing with agitation, centrifuging, and tumble drying. These states are difficult to identify, define and reproduce as friction and the
## Table 2.2

### Summary of research work on the spirality of single-jersey fabrics from 1934 onwards

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Author/s</th>
<th>Year</th>
<th>Types of yarns</th>
<th>Variables used</th>
<th>Conclusions</th>
</tr>
</thead>
</table>
b. Courses per inch  
c. Steam set  
d. Water set  
e. Reverse Twist  
f. Two ends of same twist  
g. Doubled yarns | Spirality is prevented by setting and water setting is effective - will not be evident if the single yarns have equal and opposite twists. Suitably balanced two-fold yarns lead to fabric free from spirality. |
| 2.      | Davis and Edwards | 1935 | Cotton: 1/8", 1/16", 1/32"  
Needle: Latch, bearded needle | a. Twist  
b. Courses per inch  
c. Different machines  
d. Yarn mercerisation | Spirality increases with the fineness of the machine gauge; mercerisation is more efficient. |
| 3.      | Centre de Recherches de la Bonneterie | 1969 | Unknown | Steaming or conditioning of yarns | This treatment reduces the angle of spirality, but does not eliminate it. |
| 4.      | Carnaby | 1973 | Woollen yarn: R55/2 tex ST | Knitting tension varied from 0 to 600 mN | Opines that yarn tension plays a crucial role; spirality can be reduced by increasing the cover factor, reducing the yarn twist or steaming the packages of yarn before knitting. |
| 5.      | Lord, Mohamed and Aigaonkar | 1974 | P/C yarns: Ring and Rotor | Percentage of polyester varying | Increase in polyester percentage increases the spirality of fabrics. Rotor yarns lead to a reduction in spirality. |
| 6.      | Chow    | 1976 | Unknown | Torque and spirality | |
### Table 2.2 (continued)

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>7.</td>
<td>Harrowfield</td>
<td>1981</td>
<td>Woollen: 37, 74, 111 tex</td>
<td>Twist factor 20-65</td>
<td>Suggests that a reference curve could be provided to predict ply twist required to produce plain knit free from spirality given only the single twist factor.</td>
</tr>
<tr>
<td>8.</td>
<td>Bennett and Postle</td>
<td>1981</td>
<td>Woollen: 37, 74, 111 tex</td>
<td>Twist factor 20-65</td>
<td>Criticise Harrowfield's work that the cover factor of his fabric is 11.7 tex f.42</td>
</tr>
<tr>
<td>9.</td>
<td>Buhler and Haussler</td>
<td>1985</td>
<td>Cotton: 20(^\circ), ring and rotor spun yarns. Viscose: Filament 16.7 tex f.42</td>
<td>a. Effect of no. of feeders b. Effect of Coulier region c. Effect of Coulier angle d. Effect of the sinker ring setting e. Effect knitting direction f. Effect of stitch length g. Effect of fabric takedown h. Effect of yarn twist i. Effect of the snarling tendency j. Effect of yarn doubling k. Effect of using monofilaments l. Effect of twisting of monofilaments m. Use of viscose filament yarn with twist n. Effect of neutral twist in the yarns</td>
<td>1. Rotating the knitting machine has no effect on the spirality. 2. Stitch density affects the skew. 3. Yarn twist has the greatest effect on skew. 4. Cottons of different classes do not seem to have any effect on the spirality. 5. Stiffer yarns cause a more pronounced skew. 6. Steaming the cotton yarns reduce the skew. 7. &quot;S&quot; and &quot;Z&quot; twisted yarns are knitted as plated, the skew is zero. 8. Opine that neutral twist yarns construction can bring down skew but this is expensive.</td>
</tr>
<tr>
<td>Sl. No.</td>
<td>Author/s</td>
<td>Year</td>
<td>Types of yarns</td>
<td>Variables used</td>
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</tbody>
</table>
| 10     | Alaiban            | 1986 | Roto yarn: 10", 15", 20", 24"  
Twist factors: 3.5, 4.0, 4.5  
Machine dia:3.4 inch  
Gauge: 14,16,18,20 | 1. Effect of gauge  
2. Effect of twist     | Loop shape, twist liveliness, slackness of construction and coarseness of machine all influence spirality.  
Twist lively yarns have to be knitted as tight as possible on a machine of finest possible gauge.  
Yarn mercerisation reduces spirality. |
| 11     | DeAraujo and Smith | 1989 | Cotton PVC: (18-36") Ring, rotor, air jet, friction spinning.  
Treatments were given to yarns.  
Machine dia:2½"  
Gauge:20 | a. Different types of yarns such as ring, rotor, friction and air jet.  
b. Blend composition.  
c. Yarn treatments such as PVC (polyvinyl alcohol).  
d. Number of feeders.  
e. Using LMP (low melt polyester) with cotton.  
f. Heat setting of LMP + cotton yarns.  
g. Steam setting | 1. Rotor spun and air jet yarns produce fabrics with a low degree of spirality.  
2. Friction spun yarn from 100% cotton produced highest spirality.  
3. P/C 50:50 have a lower tendency to produce spirality than 100% cotton.  
4. With air jet and rotor 50/50 blend, no spirality was noticed. While ring spun produced maximum spirality.  
5. Wet hot treatments reduced spirality.  
6. Multified circular knitting machines rotating counter clockwise will produce wales inclined to the right and machines rotating clockwise will produce wales inclined to the left.  
7. Three-thread fleece fabrics can be knitted with substantially reduced twist directions as the binder and ground yarns. |
### Table 2.2 (continued)

<table>
<thead>
<tr>
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</tr>
</thead>
</table>
2. Spirality can be reduced by using a treated yarn and knitting to a sufficiently high tightness, preferably with \(d/l > 0.06\). |
| 13.     | Primentas | 1991 | Cotton | Twist liveliness | Spirality is affected by twist liveliness |
| 15.     | Kimmel and Sawhney | 1995 | Staple Core-yarn and cotton ring spin yarns. 3.5" (88.9 mm) 20 gauge single feed jersey knitted | Direction of twist and processing conditions, such as scour, wash | 1. Spirality is found to be high in fabrics knitted from staple core yarn compared to 100% ring spun yarns.  
2. Spirality tends to decrease with wet processing for both the types. |
| 17.     | Jiang Tao, Dhingra, Chan and Abbas | 1997 | Cotton ring spun yarns | Range of yarn counts, yarn twist, fabric tightness factors | The study has revealed that yarn twist and fabric tightness factor are the most predominant factors contributing to fabric spirality. |
| 18.     | Tavanai, H, Denton and Hepworth | 1997 | Flat and Textured yarns | Balanced and twist-lively yarn torque yarn retraction | Spirality is influenced by yarn torque.  
Extensibility is influenced by yarn torque. |
The twist multiplier, yarn count and tightness factor are the principal factors to influence on spirality. The relation between spirality and tightness factor in plied cotton yarn shows the reverse trend in comparison with single cotton yarn. The plied yarns have the advantage of minimizing of spirality.

Spirality is reduced in singed yarns. Spirality is affected by twist liveliness. Air jet yarns show lower angle of spirality.

### Table 2.2 (continued)

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<th>Variables used</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.</td>
<td>Shin Woong Park and Sang Weon Lee</td>
<td>1998</td>
<td>Cotton</td>
<td>Types of yarn count and various twist multipliers</td>
<td>The twist multiplier, yarn count and tightness factor are the principal factors to influence on spirality. The relation between spirality and tightness factor in plied cotton yarn shows the reverse trend in comparison with single cotton yarn. The plied yarns have the advantage of minimizing of spirality.</td>
</tr>
<tr>
<td>20.</td>
<td>Kurup</td>
<td>1999</td>
<td>Cotton yarns</td>
<td>Effect of Singeing</td>
<td>Spirality is reduced is singed yarns.</td>
</tr>
<tr>
<td>22.</td>
<td>Punj, Mukhopadhyay and Chatterjee</td>
<td>2000</td>
<td>Ring and airjet acrylic and viscose yarns</td>
<td>Twist and Relaxation</td>
<td>Air jet yarns show lower angle of spirality.</td>
</tr>
<tr>
<td>23.</td>
<td>Denton</td>
<td>1966</td>
<td>Poy</td>
<td>Twist</td>
<td>Spirality of fabrics plain-knitted from singles false-twist yarn decreases as the bulking twist increases through the normal practical range of twists.</td>
</tr>
</tbody>
</table>
mechanical properties of the fibres, yarns and structures can create high internal restrictive forces and thus inhibit recovery.

The dimensional changes or shrinkage will affect the suitability of knitted garments for specified end use. For reliably predicting the dimensional properties of finished knit goods, "STARFISH" (start as you mean to finish) programme was developed by International Institute for Cotton, Manchester, England. The programme is based on many reference states and provide a huge database for predicting the final dimensions of the fabric of any quality. However, the programme cannot predict handle, appearance and aesthetic qualities of fabrics which are very important from consumer point of view. Knitted fabrics in grey state are not ready to use by the consumer. They have to be prepared to impart whiteness and then subsequently dyed or printed.

Any finish which improves the desirable property of knitted fabrics is welcome. During chemical processing, owing to various external forces addition of chemicals, stress relaxation, shrinkage and friction can occur. Each one of these produces a change in fabric property. Some fibres on the yarns of fabric surface get abraded, and some fibres are even extracted out, thus the original yarn structure is changed. Owing to the effect of chemical reagents, surface roughness and friction change drastically. In many cases, the finish has multiple purpose. For example, cross linking finish reduces the reversible elongation of the fibre, thereby imparting the crease resistance and dimensional stability to the fabric. The resin crosslinks intermicellar locations and brings about changes in mechanical properties.

This section deals with some work which has been reported on the chemical treatments which have been given to the knitted fabrics, in particular weft-knitted fabrics.
Kovotic (1996) has studied the influence of alkali pretreatment on cotton knitted fabrics before and after peroxide bleaching. Optimum results could be achieved with sodium hydroxide at 60°C. Higher whiteness could be achieved at higher temperature, but at the cost of degradation of knits.

Phukan and Subramaniam (1995) have investigated the effect of finishing treatments on cotton and cotton blended plain knitted fabrics. They observed that finishing treatments did not improve the degree of flat set, but they improved aesthetic properties of appearance and handle.

Biopolishing of fabric with enzyme cellulase is the most recent development in finishing technology. It weakens the small fibre ends protruding from the surface, which are removed by mechanical action. The technology is eco-friendly and encouraging results have been reported by investigators.

Pedersfn et al (1993) have shown that 100% cotton knits when treated with 3.0% acid cellulase do not exhibit pilling. The effect was permanent, and did not diminish even after several washes. The loss in strength can be minimised by using 1.2% enzyme for a period of 40 min.

Koo and others (1994) studied the effect of rate of enzymatic hydrolysis on knitted and woven fabrics. Enzyme treatment significantly reduced the tear strength and dye uptake. The strength loss increased with increase in reaction time.

Snyder (1997) studied the effect of cellulase enzyme treatment on tubular and open width cotton knits at different stages of processing. The treatment improved the surface and visual appearance of all fabrics. The treatment was found to be durable to laundering the strength of the fabric reduced by about 25%.
Varma et al (1986) applied cross-linking treatments to overcome poor functional properties of knitted goods of plain, interlock and rib structures made from cotton. They concluded that mild cure (new) catalyst system exhibited lower extent of resin migration vis-a-vis better distribution of cross links resulting in better physicomechanical properties.

Factors affecting dimensional properties of grey and crosslinked cotton knitted fabrics were studied by many investigators.

Frick and Verburg (1976) observed that laundry shrinkage in knitted fabrics of cotton and cotton polyester was reduced by a combination of chemical crosslinking and pre-shrinkage treatments.

A detailed study conducted by Lo (1989) on shrinkage of cotton knit goods under STAR FISH programme revealed that five wash and tumble drying cycles were sufficient to reach reference states.

Sin (1989) opined that STAR FISH programme could not predict fabric appearance and handle.

2.12 RELAXATION OF THE KNITTED FABRICS

During knitting, the fabric is subjected to strains that relax when the fabric is removed from the machine. If no wet treatment is carried out, the resulting change in dimensions is said to be due to 'dry relaxation'. Wetting out the fabric changes the fabric dimensions further and this is called wet relaxation. Additional dimensional changes occur when the fabrics are agitated as in the initial stages of washing and these changes are referred to as 'consolidation shrinkage'. Nutting (1961) explains that the relaxation process changes the intermolecular structure inside the fibre and helps relieve the torque stored inside the fibre. Munden (1959) adds that, the yarn going to the fabric is subjected to high strain during the knitting
operations, and if the fabrics were allowed to dry relax after knitting, yarns relaxed to a considerable extent and relaxed further on wetting. Accordingly he defined two states of relaxation of plain knitted fabrics as dry relaxed and wet relaxed states.

Doyle (1953) established relationship between stitch density and loop length for a number of plain-knitted fabrics only in dry relaxed state.

Postle (1968) worked on various knitted fabrics produced from various fibers and experimented on various relaxation process so as to establish a standard complete relaxation treatment that would bring loops to a dimensionally stable state. He expected wetting with gentle agitation for 30 minutes at 100°C followed by tumble drying at 80°C for 15 minutes would bring all loops to a state where they do not have any tendency to change in shape or in properties and fabric tightness factor.

Munden (1959) showed that the natural shape of loop was determined by minimum energy conditions. He worked on different types of fabrics like cotton, wool, wool-nylon, and wool-acetate. He said that, the area of the fabric, its knitting quality expressed either by a length or on area measurement, and its weight are related to and depend on the configuration and dimensions of a single loop. The geometry of knitted fabric, therefore, basically is a study of the geometry of knitted loop. He assumed that projected shape of the plain-knitted loop on to the fabric plane was that of an elastica based on which he derived geometrically the well known relations or k-values which control the quality of a knitted fabric. These k-values are related to the structural variables of plain knitted fabrics by following equations.

\[ k_w = w \times l \]  \hspace{1cm} (2.13)
\[ k_c = c \times l \]  \hspace{1cm} (2.14)
\[ k_s = k_w \times k_c \]  \hspace{1cm} (2.15)
where \( l \) = loop length, and \( c \) and \( w \) are courses and wales per inch respectively.

Shinn (1955) computed the stitch length in jersey fabric in terms of yarn diameter using an engineering approach.

Leaf (1960) proposed two mathematical models of the plain knitted loop to describe the dimensional properties of a plain knitted fabric. His models were based on simple elastica theory.

Nutting and Leaf (1964) proposed a generalized geometry of weft knitted fabrics in which they introduced a term involving yarn diameter.

Grosberg (1966) reviewed the work on the structure and geometry of yarns and fabrics and concluded that the geometry of warp and weft knitted loop depended on certain mathematical parameters and not on processing variables. He further concluded that loop length could be controlled by adjusting the rate of feeding of yarn to machine, and that the loop-shape is determined only by the length of yarn in it.

Postle and Munden (1967a) realized that the models of the relaxed plain-knit structure proposed by previous workers were based on the assumption of some geometrical shape for the knitted loop, where forces and couples applied to one loop by its neighbour were not taken into consideration. The authors considered the dry relaxed knitted loop configuration as a function of a system of localized forces and couples acting on the loop at the interlocking points in the fabric. They assumed the loop to be two-dimensional and analysed its shape as a function of the forces acting in the plane of the fabric. They showed that the geometry of the plain knit structure could be completely specified by the value of loop angle and interlocking angle, and that the fabric dimensional parameters can be expressed as functions of these angles.
The same authors extended the two-dimensional analysis of the dry relaxed knitted loop to three-dimensional structure, by considering the effect of couple tending to bend the loop out of the fabric plane. They evaluated the knitted fabric parameters, and cover for 3-dimensional structure and investigated the conditions of jamming. They showed that very high torsional strains were induced in the arms of loop from the distribution of curvature and torsion along the loop.

Postle and Munden (1967b), in their analysis of dry relaxed knitted loop configuration, concluded that the geometry of a plain-knitted structure was completely specified by the loop angle (α) and the interlocking angle (β), the value of loop angle determining the shape of the loop and the interlocking angle determining the point on the loop at which interlocking occurred.

The search for a fully relaxed (minimum energy) fabric has been extensive. Doyle (1953), Munden (1959) Nutting and Leaf (1964), Grosberg (1966), Postle (1968) and Knapton et al (1970ab) are amongst those who have made empirical or theoretical contributions to present day knowledge, and the subject has been carefully reviewed (Wool Science Review, 1972). Munden (1959), in his paper stated that it was generally appreciated that a static wet relaxation treatment for hydrophilic fibres was sufficient to relieve the stored strains and bring the structure to a strain free configuration. In a later paper (1960a), he stated that although a static wet relaxation for hydrophilic fibre fabrics was generally accepted as an effective treatment to relieve the stored strains, achieving a stable fabric may be hindered by frictional constraints, and therefore agitation during washing and tumble-drying should facilitate the process of achieving a dimensionally stable fabric. Centre de Recherches de la Bonneterie (1964) in France, reported that a wet relaxation with agitation for cotton fabrics induced complete relaxation. Knapton et al. (1968b) criticised the work of Munden and others and have said that the "stable states" of a fabric as defined by
Munden are not states at all, and therefore are not commercially meaningful and reproducible. Further, they have suggested that a fully-relaxed state is achieved by a static wet-relaxation treatment for 24 hr at 40°C, followed by a brief hydro-extraction and tumble-drying for 1 hr at 70°C. Since then several wet-relaxation methods for achieving a dimensionally stable fabric have been suggested. There may be several other factors which present problems in reaching such a state in practice.

Recently, a method which is known as Quickwash Plus has been introduced which is meant for measuring the shrinkage of weft-knitted fabrics. This takes very little time to determine the shrinkage.

Knapton and Fong (1971) suggested that fibre properties and not yarn properties were the sources of secondary effects on the dimensions of the fabrics. They found that $K_c$ was significantly dependent on the fibre quality but $K_n$ was not. They further proved that a fixed loop configuration existed for a completely relaxed weft knitted wool fabric and dimensional stability could be guaranteed within normal tolerances for such fabrics.

Knapton and others (1968b) have shown that for the plain jersey structures produced from wool and possibly for most others, fabrics tightness does not influence the parameters governing the stable fabric dimensions. Loop-length together with run in ratio for double jersey structures was found to be the fundamental parameter determining the stable linear dimensions. It was also shown that the well known relations $k_c = C \times l$ and $K_n = W \times l$ could be used to predict stable fabric dimensions.

Knapton et al. (1975ab) studied the dimensional properties of cotton and wool fabrics covering a tightness range of 10.5-18.5 and showed that the stable loop geometry of wool and cotton plain jersey fabrics were almost identical, and that fabric tightness played little role in determining the linear dimensions of the completely relaxed fabrics. But the geometrical
fabric thickness and bulk density were found to be dependent on fabric tightness. Their investigations also revealed that both mechanical and chemical relaxation processes have led to stabilisation of dimensions by allowing yarn to bulk, which has led to three dimensional changes in loop shape and consequent relaxation shrinkage.

Shanahan and Postle (1970) analysed theoretically the structure of plain knitted fabric. They concluded that there is a minimum energy configuration, fairly independent of fabric tightness and yarn properties. The actual energy minimum was found to be fairly shallow and therefore in practice some deviations from these results are to be expected.

Hurley and Duby (1967) studied the geometric changes which take place under relaxed conditions. They found that loop shape factor changed in the direction of equilibrium value 1.3, as reported by Munden. However, this value could be obtained only in the case of fabric with smallest stitch length.

Shanahan and Postle (1974a) analysed theoretically the reaction forces and couples acting within the fabric. They assumed that knitted structures are largely determined by geometrical restrictions on relative loop position without change in the basic loop shape. They showed that 1 x 1 rib structure is an inherently width-jammed structure. Similar considerations also apply to other rib and related structures.

Hepworth and Leaf (1970) have pointed out that the dimensions of the loop and hence the K-values were critically dependent on loop shape and contact region.

The empirical studies of knitted wool fabric structures by Knapton and Fong (1971) led to the conclusion that there existed a fixed configuration of the knitted loop or structural knit-cell, when the fabrics
were completely relaxed. Then loop length was only parameter which had affected fabric dimensions and tightness did not influence it any longer.

Wolfaardt and Knapton (1971) made theoretical analysis of three-dimensional, structural knit cell of all wool 1 x 1 rib structure by assuming that its configuration was geometrical, and was based on the classical elastic shape. It was revealed that the dimensional behaviour of tumble relaxed 1 x 1 rib structure was similar to that of plain knitted structure, and K values could be obtained for these fabrics by using the same equations used for plain knits.

Burnip and Abbas (1973) derived a formula to predict dimensions of weft knitted fabrics produced from a wide range of blended yarns (blends of cotton with fibre, vincel 6'4, nylon 6.6' courtelle and terylene). Recently, Jeddi and Otaghsara (1999) tried to validate their formular to the interlock fabrics produced from open end blended yarns (Polyester and cotton).

Banerjee and Alaiban (1988) have studied the geometry and dimensional properties of plain loops made of rotor spun cotton yarns. Their study revealed that area constant $K_a$ and linear constants $K_x$ and $K_w$ were not tenable. Fabric dimensions depended not only on loop length but also strongly on tightness factor and relatively weakly on machine gauge and yarn linear density.

The same authors further established that the classical expressing of loop-shape factor ($a/w$) is not a true representation of loop shape. They incorporated the degree of bending of a loop into the third dimension in an expression of loop-shape. Thus their modified shape factor was given by product of the ratio of wales to course spacings and the thickness of fabric to diameter of the yarns.

Lo (1989) suggested a method for calculation of 'k' values for cotton knitted fabrics and gave an equation which is different from that
given by Munden (1959). He said that, in unrelaxed state, regression line gave intercept which may be regarded as degree of relaxation.

2.13 DIMENSIONAL STABILITY AND SHRINKAGE

Dimensional stability of weft knitted fabrics is a serious problem in view of fabric quality control. Therefore many studies have been reported on the changes taking place in geometry and dimensional properties of weft knitted fabrics due to washing and other treatments. Though most of the work has been carried out on plain weft knitted wool fabrics, some data is available on cotton blended fabrics as well as on other weft knit structures.

Fletcher and Roberts (1953), studied the geometry of certain plain and rib knit fabrics made from cotton. They observed that the yarn in finished fabrics shrank a negligible amount in laundering and hence contributed very little to the dimensional change of the fabric. Those finished fabrics, in which the wale and course spacings before laundering followed a parabolic relationship similar to that of the laundered fabrics, exhibited least change in length and width-fabrics having the greatest knitted stiffness shrank the most in areas.

Suh (1967) carried out a detailed study on shrinkage of cotton knitted fabrics. He showed that the lengthwise shrinkage of a plain knitted cotton fabric was partly due to loop migration and rest due to change in course curvature. For a particular yarn, as loop length increased, the shrinkage increased. He further said that the major part of shrinkage occurred in simple wetting process and drying process always promoted it further.

Hurley (1967) investigated the process of tumble drying and its effect on dimensional stability of acrylic knitted fabrics. Length, width and area shrinkages increased with increase in temperature of tumble dryer. Fabric comparison was found to contribute to walewise fabric shrinkage.
Song and Turner (1968) have extended the well established geometry of plain weft knitted fabric to half Cardigan and full cardigan relaxed structures yarns produced from worsted hosiery and found that these structures obeyed the same rule.

Wolfaardt and Knapton (1971) reported that relaxation values were independent of loop length but were dependent on the count. Their study was based on knitted samples made from wool covering a wide range of loop length. They used relaxation method which involved static soak at 40°C for 1 hr.

Knapton and Fong (1971) have studied the relaxation behaviour of different weft knitted structures made from wool. It was observed that plain knits and Swiss double-pique generally exhibited isotropic dimensional changes on wasing whereas rib and interlock structures exhibited anisotropic changes. They explained that the difference in dimensional behaviour between these structures was due to dissimilar non relaxed geometrical shapes of the individual structural units. They further studied the changes in dimensions due to multiple washing and tumble drying and observed that the area shrinkage from any stage in processing to the fully relaxed state depended greatly on loop length and changes were isotropic.

Lord, Mohamed and Ajgaonkar (1974) assessed the performance of single jersey knitted fabric, using a variety of cotton yarns and fabric relaxation procedures. They observed that the autoclaving of yarn reduced shrinkage and improved the properties of fabrics.

Somashekar and Elder (1975) studied the influence of finishing and washing treatments on the degree and stability of flatset in weft knitted cotton fabrics. They observed that the dimensional stability and stability of flat set were affected by fabric construction finish, washing and drying procedures.
Knapton and Yuk (1976) put forward a theory that dimensional stabilisation was brought about largely by molecular interactions and consequent three dimensional changes in structural knit cell. Changes in loop shape resulted in relaxation shrinkage and ultimately in stabilisation of the fabric. They found that even dry cleaning process brought about larger linear shrinkages, and that dry relaxed parameters were not affected by fibre type but wet relaxed parameters were affected, the fabrics considered are cotton punto dioma.

Frick and Verburg (1976) made a comparative study of different methods for preshrinking of cotton knitted fabrics in combination with chemical crosslinking. They found that greater strength was retained with a relaxation process after crosslinking than with compaction before or after crosslinking and that compaction after cross linking was detrimental to dimensional stability.

Guise and Jones (1967) compared different methods of cross linking silicons on wool for shrink resistant finishes. The most effective shrink-resistance was obtained when the cross linking polymer contained polar groups which presumably improved adhesion.

Little (1978) compared the dimensional parameters of untreated and polymer treated wool fabrics. He observed that the final dimensions of wool knitted fabrics were approximately same irrespective of polymer types. He concluded that the relaxation treatment was prerequisite, if subsequent dimensional changes were to be reduced to a tolerable limit.

In their study of dimensions of plain knitted fabrics knitted from worsted acrylic and cotton in various states of relaxation and with a wide range of tightness factors, Gower and Hurt (1978) found that in addition to stitch length, yarn diameter also affects the dimensions.
Fabric shrinkage was discussed in brief by Poole and Brown (1978a). According to them, the mechanism of shrinkage was a combination of several effects; viz. loop length, shape changes and degree of intermeshing changes. They pointed out that totally relaxed dimensions were not necessarily subject to the same assumptions which apply to other states of relaxation. The authors subjected rib fabrics from cotton and cotton polyester yarns to a variety of relaxation treatments. They observed that cotton fabrics had undergone greater wet relaxation shrinkage than synthetic fibre fabrics, while hot dry treatments had opposite effect. The relaxation shrinkage was found to be fibre sensitive. Consolidation shrinkage appeared to be independent of the blend constitution. Cotton rib fabrics attained similar "U" values to those reported for wool fabrics.

Under "STARFISH", programme, Heap et al. (1983) studied the dimensions of a wide range of plain single jersey, 1 x 1 rib and interlock cotton fabrics. Measurements were made on fabrics in the state as received and in reference states. They observed that the dimensions of knitted fabrics were strongly affected by the finishing process as well as by the yarn count and the stitch length. They derived prediction equations for several combinations of fabric type and finishing route. These equations were found to be capable of yielding predictions of fabric dimensions that were within normal production variation.

The effect of fabric tightness and relaxation treatments on the dimensional parameters and geometrical, thickness for plain jersey fabrics made of cotton and nylon yarns was investigated by Ryuzo Oinuma (1989). He concluded that the dimensional parameters of nylon plain jersey were found to be independent of fabric tightness and method of relaxation but geometrical thickness increased linearly with increase in fabric tightness and was dependent on relaxation treatment.
Kurt (1987) identified yarn count, knitted loop length and tension applied at various stages of finishing as variables which affect the final dimensions of knitted fabric.

Varma et al. (1980) studied the shrinkage and other properties of cotton knits to various relaxation treatments. They observed that relaxation shrinkage increased with temperature and time and that fabrics made from finer counts exhibited less shrinkage.

2.14 SHAPE OF THE LOOP IN PLAIN KNITTED FABRICS

Hepworth (1971) has studied the configuration of the yarn in plain weft knitting because of the importance of loop shape in determining fabric dimensions. The particular state of the fabric which is of interest is the relaxed state, and the meaning of this term has been discussed. Since most previous work was concentrated on measuring actual fabrics or setting up geometrical methods, she considered the yarn in the loop as an elastic rod and formulated equations of equilibrium. These were solved to obtain the shape of the loops and forces acting between them. A computer was used to solve the equations by numerical methods.

Hepworth (1971) found that for the idealised structure, fabric dimensions varied with the ratio of yarn diameter to loop length (d/l). It was found that jamming occurred between courses for values of d/l greater than 0.0313, i.e., for all except very slack fabrics. Jamming also occurred between courses for values of d/l greater than 0.059, i.e., very tight fabrics. So many assumptions such as straight, inextensible and incompressible yarn having circular cross sections were made. Equations of equilibrium were set up which were six in number, and numerical methods were used for solving them.
Konopasek (1970) quite independently used a model identical with the one described by Hepworth (1971). His results, which were compared with those obtained by Hepworth, agreed closely with them. Rather than extend his analysis to include jamming, however, he studied the case of a yarn permanently set in an arbitrarily chosen shape and, for a range of such shapes, deduced the tightest fabric for which no jamming would occur. Shanahan and Postle (1970) have also worked on the same problem. Since their analysis did not include strain-energy of compression, it was criticised by Hepworth and Leaf (1976) that it was based on false assumptions.

De Jong and Postle (1978) proposed a general energy analysis of fabric mechanics in which many of the limiting assumptions of force analysis have been removed. Jamming of the structure is considered as involving ordinary inter-yarn forces, and specific structures and deformations are treated as different boundary value conditions. The total strain energy of the unit cell of each fabric is minimised subject to constraints, using optimal theory, rather than by applying the much more widely used theory of their rods. A loop, which has the desired formation is fed into a computer whereupon the shape is manipulated systematically to arrive at the shape of the minimum energy loop, the equilibrium distributed forces acting along the loop, and the internal forces and couples applied to the fabric.

In the energy analysis, many of the limiting assumptions of previous analysis of the knitted fabric are not necessary. In particular, the nature of yarn contact within the structure and the position and direction of the internal distributed forces do not represent initial conditions of the analysis, but rather this information is a direct result of the solution of the general equations of equilibrium subjected to the boundary conditions for the plain knit structure.
Using the optimal control theory, de Jong and Postle (1977a) obtained the shape and dimensions of the loop, and the analysis was well appreciated by R.B.Hepworth (1978) and K.Hepworth (1978).

Harlock and Ramkumar (1997) have investigated the effect of knitted structural variables on the low stress mechanical properties of cotton rib knitted fabrics. Their conclusions are that the mechanical properties of fabrics influence the handle and quality of fabrics, and the structural parameters have a unique role in determining the handle. The lighter the fabric, the better the consumer ranking.

Ramkumar (1998) has dealt with the handle of 1x1 cotton rib fabrics. He has shown that yarn linear density dominates the compressional behaviour compared to loop length. Studies on the frictional properties have shown that the fabrics may be characterised by various factors including both static and kinetic frictional coefficients and other parameters derived from them.

Comparison with subjective evaluations has shown that human sensory skills are unable to discriminate between these fabric properties as reliably and as discreetly as the electromechanical transducers used in the instrumentation. Novel ideas were implemented in tribological investigations; with in vitro human skin and fabric frictional interaction studies being undertaken for the first time. Ramkumar extended further to in vivo skin and fabric interaction studies. A novel friction sensor that could mimic the human finger using polymeric materials was developed by him, and this was used in the Kawabata tester which is designed for measuring the surface properties.
He has also made a comparison between the sliding friction and the Kawabata methods, and has reported that the correlation is very poor. Howell (1953) based on their fundamental work have suggested a relationship of the form.

\[
F = CP^n, \quad 0 < n < 1
\]

(2.16)

where \( F \) is the frictional force per unit area of contact, \( P \) is the normal force per unit area of contact and \( C \) and \( n \) are frictional constants. The two friction constants \( C \) and \( n \) are basically derived from equation (2.16), where \( F \) and \( P \) are measured in pressure units (Pa). Solving the above equation for physical units, it is evident that \( n \) has no unit. However, the friction constant \( C \) has a unit \( \text{Pa}^{(1-n)} \). It is clearly evident from the foregoing discussion that the friction constant \( C \) is dependent on \( n \). This dependency causes difficulty in comparing the \( C \) values of different fabrics. Furthermore, it is well known that \( n \) is a measure of the physical characteristics of the material. Thus, it is not logical to compare and characterise the frictional properties of two different textile materials using the \( C \) values. However, when the values of \( C \) are raised to the power \( 1/1-n \), comparisons are possible. This suggests defining a new constant \( K \), where \( C^{1/1-n}=K \). This new constant \( K \) is used to compare the surface mechanical characteristics of fabrics and has the same units as \( F \) and \( N \). Using this concept, Ramkumar et al. (2000) have studied the effect of loop length and yarn linear density on the static and kinetic friction of 1x1 rib fabrics produced from Cotton. The variation in the structure of the knitted fabrics is reflected in the frictional properties as defined by the new frictional constant. Static and kinetic friction values are found to be higher with 18.4 tex yarn, and lower for 14.0 tex, implying that the area of contact plays a very important role. Also, with the increase in loop length, both the coefficients show an increase, again implying that area of contact plays a crucial role.
2.15 YARN QUALITY REQUIREMENTS FOR KNITTING

Yarn properties such as count twist, moisture conditions, quality and package hardness were found to affect the characteristics of knitted fabrics.

Sankaranarayanan and Somasunder (1969) have pointed out that yarn properties such as U% and CV% of single cotton yarn strength had a significant influence on fabric appearance and stoppage of knitting machine.

With the development of open-end (OE) spinning system, Burnip and Saha (1973) investigated the dimensional properties of knitted fabrics made from OE cotton yarns. It was seen that fabrics knitted from the two types of yarns (RS and OE) possessed different properties. Aesthetic properties of fabrics made from OE cotton yarns were inferior to those of fabrics RS cotton yarns, particularly with regard to stitch clarity and a somewhat harsher handle, although the latter effect was shown to be apparently unrelated to differences in the frictional properties of the two types of yarn. They also concluded from yet another investigation that on the basis of the average loop length (K values) from which other dimensional parameters can be calculated may be used to characterise the structure under investigation.

Sasaki and Kuroda (1974) identified four yarn characteristics that had an important effect on knittability. The unwinding resistance from the supply package, yarn on yarn friction, yarn on metal friction and bending rigidity of yarn. On the basis of results obtained by them, an apparatus was made for measuring the four factors mentioned above. Measured results for various yarn using this apparatus showed high correlation to the knitting operations. However, the knittability results correlated well with yarn, irregularity and the number of thick and thin places measured with Uster Classimat.
The performance of OE, twistless and RS yarns in weft knitted cotton fabrics was studied by Lord et al. (1974). A variety of yarn and fabric relaxations were used, and it was evident that unrelieved torque was a prime cause of loop distortion spirality and fabric shrinkage. It was clear that auto claving was the best way of reducing twist liveliness and the associated difficulties in manufacturing the fabric. It was also found to improve the properties of the fabrics. Properly relaxed, RS yarn made a fabric with good appeal, acceptable strength and abrasion resistance and reasonable shrinkage. Twistless yarns gave good fabric handle, high lustre, zero spirality and little shrinkage, but there was some loss in fabric strength. Lee and Ruppenicker (Jr) (1978) observed that lower carding rates higher total spinning drafts and spindle speeds resulted in slightly stronger more uniform cotton yarns with fewer neps and other imperfections suitable for knitting.

Brown (1978) suggested that polyvinyl alcohol be used instead of wax since it acts as normal yarn lubrication for effective control of fly produced during the weft knitting of cotton yarns.

Pillai (1982) observed that yarn faults and imperfections of carded and combed cotton yarn of 40s count (ring spun) had significant influence on yarn breaks during knitting, fabric appearance and bursting strength.

Bartnik (1986a) emphasized the importance of raw material (fibre and yarn) testing for controlling the knitting performance and fabric quality.

Mechanical and dimensional properties of plain knitted fabrics made from OE and RS yarns using acrylic-viscose blends have been reported by Sharma et al. (1986).

Zurek et al. (1986) studied the tensile properties of knitted fabrics made from polyester and polyamide (twisted and textured) yarns with three
different stitch lengths. Fabrics made from textured yarn showed higher elastic recovery than the fabrics made from twisted yarns. All fabrics showed higher elastic recovery when they were stretched in the wale direction rather than in the course direction. Fabric air permeability depended on the volume and arrangement of fibres. Air permeability of textured fabrics was found to be half of the fabrics made from twisted yarns.

The effect of twist and concomitant changes of knitted fabrics particularly using combed cotton yarn was investigated by Cooke and Kamal (1986). Results of the trials using modern commercial machines and normal tightness factor were compared with the results of the testing on a knittability tester similar to that proposed by Sasaki and Kuroda (1974). There was no correlation between the knitting performance of the five twist levels and the results of the Sasaki and Kuroda (1974) test. The yarn tenacity and extension were not found to be directly related to the knitting performance of yarns. The highest positive correlation observed between fabric fault and yarn irregularity suggested that isolated weak places or knots caused press-offs that occurred with long range of yarn.

A study on the effect of twist factor and stitch length of OE cotton yarn on the properties of rib knitted fabrics by Sharma et al (1987) revealed that twist had affected the properties of knitted fabrics to a significant level. The OE yarn worked quite satisfactorily in knitting and produced very acceptable fabrics in terms of dimensional and mechanical properties. Steaming of OE yarn reduced twist liveliness which made processing on knitting machines easier.

De Araujo and Smith (1989a) have investigated the nature of spirality in both dry and fully relaxed jersey fabrics produced from a series of relaxed spun yarns. They have developed a theory to explain the mechanism of loop inclination and loop rotation in single knit fabrics. They showed that the spirality could be minimised by knitting Z-twist yarns in
clockwise direction and S-twist yarn in counter clockwise direction. They also observed that friction spun yarn made from 100% cotton produced fabrics with the highest degree of spirality followed by RS yarns. A direct relationship was found to exist between the angle of spirality, twist multiplier and the type of spinning technology used.

Based on the survey of yarns used in knitting units, Varma and Ramaswamy (1992) suggested various measures to control yarn faults such as use of optimum process parameters in spinning, better maintenance of machines and use of good yarns for improving knitting performance. Use of overhead cleaners could reduce the faults to a significant level.

2.16 MECHANICAL PROPERTIES

A brief overview of research work on the mechanical properties of knitted fabrics is given in this section.

2.16.1 Bending Properties

The bending characteristics of wool knitted fabrics were investigated by Hamilton and Postle (1976) using an apparatus which is similar to that developed by Chapman (1974). The apparatus was able to measure and record the bending stress-strain curve (bending moment vs curvature) of fabrics. They used geometrical and rheological models to calculate the bending rigidity values of fabrics. They also analysed critically the hysteresis curves for relaxed and unrelaxed knitted fabrics. Gibson and Postle (1978) studied the bending and shear behaviours of double knitted fabrics like Punto-di-Roma and Swiss double pique, and warp knitted fabrics with the help of geometrical models. They studied the bending properties of fabrics knitted from wool and polyester textured yarns using a pure bending tester. It was found that the effect of finishing treatment on knitted fabrics was less compared to woven fabrics.
2.16.2 Tensile and Shear Properties

Shanahan and Postle (1974a,b) conducted a theoretical analysis of the tensile properties of wool and nylon mono-filament plain knitted fabrics. They considered both the elastic deformation of loop and the yarn compression as possible mechanisms for fabric extension. The correlation between the experimental and theoretical initial modulus was found to be good. They also investigated the effect of relaxation treatment on the initial load - extension behaviour of knitted fabrics. They found that relaxation had very little effect on the initial modulus of knitted fabrics. A two dimensional loop model was used by them to predict the load-extension behaviour of knitted fabrics theoretically. The energy analysis technique was applied to the biaxial deformation of knitted fabrics by de Jong and Postle (1977a). They studied the nature of yarn contact and the distributed forms between interlocking loops using the energy analysis. Experimental work on the tensile properties of knitted fabrics was undertaken by Somashekhar (1975) and Hallos et al. (1990).

The work on the shear of knitted fabrics is slight compared to tensile properties of knitted fabrics. Carnaby and Postle (1974) conducted a study of the shear behaviour of plain 1 x 1 rib and interlock wool weft knitted fabrics. They used a modified version of the shear tester developed by the Fibre Institute, TNO of Delft. They have mentioned about the parameters. The objective bending measurements were discussed in terms of the geometrical changes occurring within the unit cell of the knitted fabrics. They found that the low shear resistance of knitted fabrics was due to large frictional restraints and low resistance to fibre slippage. Hamilton (1975) conducted a detailed study on the shear behaviour of single and double Jersey knitted fabrics.
2.16.3 Compression Properties

Postle (1971a,b) studied the lateral compression property of plain knitted fabrics made of different types of yarns. He applied a general geometrical model based on the assumption of constant unit cell configuration to derive simple relationships for effective diameter and specific volume of yarn as it exists within the fabric, the fabric thickness and the bulk density of knitted fabrics. He found that the thickness-pressure relationship was non-linear. Williams and Leaf (1974) studied the thickness of plain knitted cotton fabrics. They studied the compression and decompression property of knitted fabrics using a thickness gauge. They established a pressure thickness relationship of the form \( T = a + b \exp(-kP) \) where \( T \) is the fabric thickness, \( P \) is the pressure on the fabric, and \( a, b \) and \( k \) are constants. In the recent past, many researchers have utilised the Kawabata compression tester to study the compression properties of knitted fabrics. Pau-Lin Chen et al. (1992) have used the KES-FB3 tester to study the compression properties of a set of knitted fabrics.

The availability of the Kawabata set of equipment has made it possible to measure the low stress mechanical properties of knitted fabrics. Chen et al. (1992) have carried out the evaluation of handle of 50:50 cotton polyester open and yarns. Hallos et al. (1990) have carried out the evaluation of handle of a set of double jersey fabrics made from spul polyester wool and textured polyester. They compared different fabrics using polar profiles derived from the subjective and objective results. Begum (1994) has carried out a study of low stress mechanical properties of plain knit fabrics produced from ring and double-rove and rotor spun polyester cotton yarns. Fabrics made from ring and double rove yarns were found to be softer than fabrics made from rotor yarns. Gong (1995) has carried out a study of the low stress mechanical properties of 1 x 1 rib knitted fabrics made of acrylic, cotton and wool. These fabrics were subjected to fifty laundering cycles, and the mechanical properties were...
evaluated. Principal component analysis (PCA) was used to analyse the results, and the results were represented in the form of vector maps.

It is clear from the survey of literature that research work on handle of knitted fabrics is scant compared to the vast amount of information available on the mechanical properties of woven fabrics.

Changes that occur in acrylic, cotton and wool knit wear fabrics as a result of repeated laundering have been successfully quantified by both subjective evaluation of appropriate fabric sensory attributed and objective measurement of mechanical properties. The sensory property changes are related to dissatisfaction expressed by consumers with the wash-wear performance of many knit wear fabrics, and also provide much more detailed information than typical consumer studies (Mackay et al. (1999)).

Changes in some of the objectively measured fabric mechanical properties are related to specific physio-chemical changes, occurring at the fibre's level in the wool, cotton and acrylic fabrics. Mackay et al. (1999) believes in using PCA (Principal Component Analysis) to provide overview on the subjective and objective data. Specific changes in the three fibre types made by the laundering process have been attributed to variables such as agitation level, detergent product and drying method.

It is suggested that PCA of the combined, subjective and objective data provides a means expressing fabric sensory attributes in terms of selected objective measurements and of defining a total hand value for any fabric sample. This approach obviates the need to drive THVS from HVS (or from objective measurements) by using regression equations based on "once - and for - all" expert judgement on 1 x 1 rib reference fabrics.
Park and Hwang (1999) have developed a simple and practical hand evaluation method to calculate the new overall hand value using seven mechanical properties, and this has been compared with the total hand values (THV) obtained from KES-FB system. Double weft knitted fabrics consiered are interlock, royal interlock and mock royal interlock from. By using fuzzy transformation matrix, the mechanical and physical, properties of the double weft knitted fabrics, namely tensile, bending shear compressional and surface properties have been analysed; these knitted fabrics differ in structural aspects. It has been concluded that the total yarns hand value predicted on the basis of fuzzy transformation matrix is quite accurate. The alternative method resulting from the principal mechanical properties (EMT, RT, RC, MIU, W, B, 2HG), it has been pointed out, will provide researchers with a simple hand test method for double knit fabrics. Park and Hwang and Kang (2000) have also applied fuzzy logic and neural networks to total hand evaluation of knitted fabrics.

Quaynor et al. (1999) have reported on the dimensional changes in knitted silk and cotton fabrics following laundering process. Both plain and 1 x 1 rib fabrics were considered and they were subjected to relaxation process and an extended series of wash and tumble dry cycles changes in dimensions have been measured after every process and cycle.

Statistical analysis of the experimental data reveal the effect of yarn type as well as linear density and tightness factor on the linear and area shrinkage behaviour of silk as compared to cotton. It has been found that cotton shrinks more than silk, and silk rib units stretch excessively in width. Silk attains full relaxation after one laundering cycle, and it has been pointed out that it is possible to predict fabric dimensional changes with wet relaxation as well as with laundering especially in silk.

Quaynor et al. (2000) have investigated the effects of laundering and laundering temperatures on surface properties and dimensional stability for plain flat, knit, silk, cotton and polyester fabrics with varying cover factors. The fabrics are subjected to relaxation processes and an extended
series of wash and tumble dry cycles in laundering baths of various temperatures. Dimensions, surface friction and roughness of fabrics have been measured in every process. Changes in dimensional stability and surface properties with relaxation processes and laundering temperatures are classified. Relations existing between frictional motion and structural parameters have been discussed.

The results show that the dimensional stability of silk is sensitive to a particular temperature. Highest shrinkage is recorded with slackly knitted cotton at the highest temperature which is a well known phenomenon. There is a considerable effect of wet relaxation on the dimensional stability as well as surface properties. Silk’s, coefficient of friction is the highest, and the lowest surface friction occurs at the highest temperature. Slackly knitted fabrics also display higher friction than those of tightly knitted fabrics. The coefficient of friction has a tendency to decrease with increasing tightness, while the surface roughness shows an opposite tendency. There is a good correlation between stick slip motion and ribs on the fabrics.

Jeddi and Otaghsara (1999) have investigated the effects of yarn twist and fibre percentage in blends on the dimensional properties of the interlock structure. A series of interlock, weft knitted fabrics was produced from open end cotton polyester blended yarns with different yarn twist, loop length, fibre percentage in blend, and a variety of relaxation treatments. A comprehensive experimental analyses show that the Ks value (stitch density multiplied by the square of loop length) is related to yarn density, fibre percentage in blends, and relaxation treatments. They have concluded that the correct relaxation state for cotton fabrics to reach the maximum shrinkage is full mechanical relaxation, and for cotton polyester blended and 100% polyester fabrics is chemical relaxation. The empirical results show that the effect of mechanical relaxation decreases as the percentage of polyester in blends increases.
Tavanai, Denton and Hepworth (1997) have investigated the effects that retraction and torsion in fine textured yarns have on knitted structure and extensibility. Yarn torque, apart from causing spirality in plain - knitted fabrics, also leads to other effects. Loop distortion, as a result of yarn torque and the contribution of retractile power and twist liveliness of fine false-twist textured nylon yarns to geometrical parameters and extensional properties of single and two feeder plain knitted fabrics have been investigated. A model to represent the structure of plain knitted fabrics from such high-torque hosiery yarns has been put forth. Twist liveliness affects both geometrical parameters and the extensional properties of plain knitted fabrics.

Morooka et al. (2000) have reported a very interesting study on the compressive properties of panty hose fabrics knitted from nylon, silk and polyurethane fibers. Different kinds of panty hose fabrics were studied from cylinder - elongation experiments and wear experiments. Compressive properties, which include compressive energy, compressive resilience and fabric thickness, were found to differ remarkably according to the types and the sites of hose and posture while being worn. The pantyhoses were extended to different levels, and the compression properties have been examined. There is some semblance of this work already done by Thirlwell and Treloar (1965) on the non-woven fabric.

2.17 THE HANDLE OF FABRICS
2.17.1 Introduction

Textile scientists have made a considerable progress in objectively measuring handle of fabrics. A major upsurge in research on handle measurements took place due to the pioneering work of Professor Kawabata of Kyoto University. A brief overview of the handle of fabrics is given.
2.17.2 Fabric Handle

The term fabric handle has been defined in various ways such as

a) the quality of a fabric or yarn assessed by the reaction obtained from the sense of touch
b) the sum of sensations expressed when a fabric is handled by touching, flexing of fingers and so on.

Lundgren (1969) has defined as the summation of weighted average contributions stimuli evoked by fabric on major sensory centres.

There are two methods which are very popular in handle measurements. They are the subjective and objective test methods.

2.17.3 Subjective Measurements

The evaluation of fabrics by judges for quality attributes such as stiffness, softness, resilience etc in some order is the principle behind the subjective evaluation of fabrics. These are basically two main categories in subjective evaluation. They are:

2.17.3.1 Magnitude Estimation

It is based on awarding a score, to each quality attribute of the fabric on an arbitrary scale.

2.17.3.2 Ranking Method

This method involves comparing two different fabrics for handle as a whole or each individual attribute of the fabric and giving the preference.
2.17.4 Previous Work on the Subjective Evaluation of Handle

Binns (1926a) conducted a systematic study on the subjective evaluation. He employed both experts and non experts within the wool trade to evaluate fifteen different fabrics made from three different lots of wool. He found that both the trained and untrained judges had a tendency to use both vision and touch to evaluate the fabrics. He published a psychologically based analysis of handle. In this study, the subjects were asked to grade the cloths by sight alone for "smartness of appearance" by touch alone for "softness of handle" and by full judgement on a commercial basis and in the case the judges buy the fabrics. An important conclusion which he arrived in this study observing the way in which the judges judge the fabrics was that the final discrimination and evaluation was determined by the sense of touch. He also carried out a comparative study between the judgements of individuals skilled in the textile trade and the natural judgements of untrained adults and children. The results of the study suggested that the experts', judgement were based upon an appreciation of the material due to the special and intensive training on the intricate technical features about the cloth. The judgement of children and untrained judges is based upon the sensory factors which are in immediate and direct liaison with the senses of touch and sight. Binns (1926b) comprehensive study of subjective evaluation dealt with all aspects of the subjective evaluation of wool textiles. Vaughn and Kim (1975) and Ellis and Garnsworthy (1980) have reviewed various handle evaluation methods. More recently, Slater (1997) has reviewed the subjective testing methods in textiles. Stearn et al. (1983) used an international panel of judges consisting of experts and consumers to analyse the handle of fabrics. Mahar (1988) conducted subjective evaluation of handle of a set of 87 winter style suiting fabrics assembled in Australia. Gong (1995) used the expertise of experts in a finishing factory to rank the knitted fabrics for their handle properties. Recently; Mackay (1992) has used the sensory evaluation panel co-ordinated
by the sensory science unit of the Unilever Research Laboratory to evaluate the handle of characteristics of a set of 1 x 1 rib knitted fabrics. The panelists used a set of ten tactile descriptors which are given on Table 2.3. The average scores from a panel of 20 judges were used for ranking the fabrics.

**Table 2.3**

*Handle Descriptors Used by Mackay et al. (1999)*

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Handle Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Softness</td>
</tr>
<tr>
<td>2.</td>
<td>Flexibility</td>
</tr>
<tr>
<td>3.</td>
<td>Stretchiness</td>
</tr>
<tr>
<td>4.</td>
<td>Thickness</td>
</tr>
<tr>
<td>5.</td>
<td>Smoothness</td>
</tr>
<tr>
<td>6.</td>
<td>Greasy feel</td>
</tr>
<tr>
<td>7.</td>
<td>Man made feel</td>
</tr>
<tr>
<td>8.</td>
<td>Warmth</td>
</tr>
<tr>
<td>9.</td>
<td>Bounciness</td>
</tr>
<tr>
<td>10.</td>
<td>Felting</td>
</tr>
</tbody>
</table>

More recently, Talebpoo (1996) has carried out the subjective evaluation of a set of cotton fabrics with different finishing treatments. The judges were asked to evaluate the smoothness of the fabrics. The judges ranked the fabrics and the ranking were compared with the measured frictional values. The static and kinetic coefficients of fabric friction were increased by easy care finishing with DHDMI but were decreased by the application of a silicone softener. The latter was found to be highly effective in maintaining a low surface friction even when higher DHDMI add-on was used.
It is clear from the foregoing discussions that the subjective evaluation of handle depends on subject’s mental state, education, experience in a particular trade. Therefore extreme care has to be taken in selecting the judges to evaluate the quality of fabrics. Furthermore, caution should be exercised in choosing the subjective test methods. In general, paired comparisons technique can be considered as a reliable test method.

2.17.5 Objective Evaluation of Fabrics

Peirce (1930) pioneered research on the objective evaluation of fabrics. In his classical paper, "The Handle of cloth as a measurable quality", he attempted to measure the mechanical properties of fabrics such as stiffness and compression. However, he did not attempt to measure the frictional properties of fabrics. He characterised the handle sensation with the help of eight measurable mechanical properties such as:

1) bending length
2) flexural rigidity
3) thickness
4) hardness
5) bending modulus
6) compression modulus
7) density and
8) extensibility

Following the earlier attempts of Peirce (1930), many researchers have tried to devise physical test methods that can correlate well with the sensation of the feel of fabrics. Dreby (1942) considered pliability, smoothness and fullness to be important to the handle of fabrics. His result showed that the more the flexibility compressibility, the smoother the fabric, and vice versa. It is evident from the experiments of Peirce (1930) and Dreby (1942) that there has been a great interest to correlate the sensation of feel with the mechanical properties of fabrics.
Vaughn and Kim (1975) outlined different objective test methods for the parameters associated with the handle of fabrics. They measured twenty different mechanical properties of fabrics and expressed handle in terms of their mechanical properties. The mechanical properties considered by Vaughn and Kim (1975) to be important for the evaluation of handle of fabrics are shown in Table 2.4.

Table 2.4

Mechanical Properties considered by Vaughn and Kim (1975)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Mechanical Property</th>
<th>Measurable Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Elastic Flexural Rigidity</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Bending Hysteresis</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Bending Loop softness</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Bending Bending length</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Bending Bending Recovery</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Drape Drape coefficient</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Shearing Shearing stress</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Shearing Shearing width</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Shear Shearing Recovery</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Initial Shear Modulus</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Shearing Shearing Recovery</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Tensile Tensile Extensibility</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Tensile Initial Young's Modulus</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Tensile Tensile Recovery</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Thickness Thickness</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Compressibility Compressibility</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Compression Hardness</td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>Compressional Resilience</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>Areal Density Weight per Unit Area</td>
<td></td>
</tr>
<tr>
<td>20.</td>
<td>Friction Coefficient of Static Friction Coefficient of Dynamic Friction</td>
<td></td>
</tr>
</tbody>
</table>
More recently, Bishop (1996), in his textile progress, has summarised different test methods which are closely associated with fabric hand. It is clearly evident from the studies of previous research workers that there is a correlation between the mechanical properties of fabrics and handle. The following section gives a brief overview of the instruments which are used for measuring low stress mechanical properties.

2.17.6 Instrumental Evaluation of the Mechanical Properties of Fabrics

In this section, a brief overview is given about different instruments for measuring the mechanical properties of textiles. A detailed description about different instruments and their developmental history has been dealt with by Chen (1995).

2.17.7 Tensile Testing

Extensibility of fabrics is considered to be an important contributor to the handle of fabrics. Measurement of the extensibility of fabrics and their tensile properties started during the early part of this century. Stanton and Booth (1910) conducted uniaxial tensile tests of fabrics. Wallen and Lewis (1916) devised the grab tensile tester for uniaxial tensile measurements. In addition to uniaxial tensile testing, fabrics have been tested basically for their tensile properties. It has been reported by Chen (1995) that Hass and Dietzius (1917) were the first to conduct a biaxial tensile test on fabrics. Uniaxial tensile testing is a popular method of measuring the tensile properties of fabrics, and a wide range of instruments are available for measuring them. Kawabata (1996) has developed a sophisticated tensile tester to measure the four stress tensile properties of fabrics.
2.17.8 Shear Testing

Dreby (1942) used an instrument called the "Planofex" to measure the distortion of fabrics on its own plane without causing any wrinkles. A large amount of work on the shear properties of fabrics was carried by the Swedish Institute for Textile Research. Morner and Eegjolsson (1957) developed an instrument to study the shear properties of fabrics is shown in Fig. 2.11. The shear tester can be conveniently used on the Instron tester. The shear force is measured as a sum of two force components. One component is the horizontal force $H_1$ which is required to maintain the equilibrium of threads at an angle $\alpha$ to the horizontal axis which is given by

$$H_1 = 2P \tan \alpha \quad (2.17)$$

The second force component is the additional force associated with the internal resistance to shear deformation which increases the vertical force $P$ at the equilibrium state $e_1$ by $\Delta P$. At the equilibrium state $e_1$

$$H_2 \cos \alpha = \Delta P \left( \frac{l_0}{l} \right) \quad (2.18)$$

Treloar (1965) developed a simple instrument too measure the shear properties of fabrics. Figure 2.12 shows the shear tester used by Treloar. The shear force $F$ is related to the shear resistance $R$ in the sample and a horizontal recovering force caused by shear strain under the normal load $W$ which is given by

$$F = R + W \tan \theta \quad (2.19)$$

where $\theta$ is the angle of inclination, Spivak (1966) later modified Treloar's equipment to make it more suitable for routine shear measurements. Hamilton (1975) used shear deformation model characteristic of "equal length of side" as a basis for his shear tester.
Figure 2.11 Morner and Eeg-Olofsson's shear tester.
Figure 2.12  Treloar's shear tester.
Owing to the complexities involved in fabricating suitable instruments for measuring the shear properties, efforts were made by many textile scientists to establish a relationship between the bias direction strains and the shear angle of fabrics. Lindberg et al. (1961) established the relationship between bias compressional strain and the shear angle of worsted fabrics. Cooper (1963) used a simple bias extension as an alternative for shear measurements. Kilby (1963) worked on a theoretical relationship between bias extension and the shear of fabrics. In the theory, he regarded a fabric as trellis which is equivalent to an anisotropic lamina which shows the Poisson's effect and two symmetrical planes at right angles to each other. The Young's modulus in a direction θ to fabric warp axis can be expressed as

\[
\frac{1}{E_\theta} = \frac{\cos^4 \theta}{E_1} + \left( \frac{1}{G} - \frac{2V_1}{E_1} \right) \sin^2 \theta \cos^2 \theta + \frac{\sin^4 \theta}{E_2} \quad (2.20)
\]

In general the shear modulus is less than the two tensile moduli \(E_1\) and \(E_2\). In the case of \(\theta = 45^\circ\), the above formula can be written as

\[
E_{45} = 4G \quad (2.21)
\]

where \(G\) is the shear rigidity of fabrics.

2.17.9 Bending Measurements

There is a repertoire of literature available on the theory of bending of fabrics and instrumental methods to measure the bending properties of fabrics. Grimshaw (1922) pioneered the measurement of the bending properties of fabrics. His method is based on the ability of fabrics to bend its own weight. Peirce (1930), as a part of his research on the measurement of handle of fabrics, developed a flexometer for measuring the
bending properties of fabrics. The bending tester developed by Peirce (1930) is used as a routine test for the measurement of handle of fabrics.

Peirce's bending tester was modified by the Shirley Institute, and the modified equipment came to be known as the Shirley Stiffness Tester.

In 1957, Eeg-Jlofsson designed the first pure bending tester as the measurement of pure bending is important to the assessment of handle. During the same period, a pure bending tester was developed by Isshi (1957) in Japan. The apparatus was designed to bend fabric samples to form a segment of a circle whose radius changed according to bending deformation. Cantilever bending tester was developed by Livesey and Owen (1964) which had the ability to measure the bending hysteresis of fabrics. Abbott and Grosberg (1966) modified the cantilever tester of Livesey and Owen. They adopted the Instron tensile tester to measure the bending tester based on the principle of Livesey and Owen's bending tester (1964). Popper and Backer (1968) modified the bending tester developed by Isshi. The instrument had electronic instrumentation. Capacitors were used which transduced the mechanical displacements into voltage inputs. These voltage outputs were proportional to the bending moment, and the bending moments were recorded automatically. Following these earlier researchers, many have adopted the Instron tensile tester to measure the mechanical properties of fabrics. Ly (1986) developed a bending device which could be used on the Instron tensile tester. Kawabata (1996), as a part of the set of Kawabata equipment, developed a sophisticated bending tester which bends the fabric over an arc of a circle.

2.17.10 Compression and Softness Measurement

Softness has been considered as one of the most important handle attributes. Percentage compression is used as a measure of softness of fabrics.
Peirce (1930) and Schiefer (1933) have developed methods to measure compression. Dreby (1942) also developed a compression meter, and used hydraulics to measure the thickness and hence compression of fabrics. Rowlands (1963) and Mackay (1992) have used Instron tensile tester for measuring the compressional properties of fabrics.

2.17.11 Kawabata Evaluation System for Fabrics

The fundamental research on the mechanical properties of textiles showed that the mechanical properties of fabrics have a profound influence on the handle characteristics of fabrics. In the early seventies, a major upsurge in the research on handle took place due to the pioneering efforts of Professor Kawabata (1982). With the help of the handle evaluation and standardisation committee, Kawabata identified primary hand values which the Japanese experts considered important for the feel of fabrics. In collaboration of with Kato Tech Co., Kawabata developed the first series of Kawabata set of instruments. KESF consists of four instruments:

- **KES - FB1**  Tensile and Shear Tester
- **KES - FB2**  Bending Tester
- **KES - FB3**  Compression Tester and
- **KES - FB4**  Surface Friction and Roughness Tester.

The concept behind the Kawabata hand evaluation system is given in Fig.2.13. There are in total sixteen different parameters obtained from the Kawabata set of equipment. Table 2.5 gives the mechanical and surface properties by the Kawabata set of equipment. Initially, the system was used for studying the handle of wool fabrics.
Table 2.5
Mechanical and Surface Properties Measured by the Kawabata set of Instruments

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT</td>
<td>Linearity of Load/extension curve</td>
<td>None</td>
</tr>
<tr>
<td>WT</td>
<td>Tensile energy</td>
<td>N/m</td>
</tr>
<tr>
<td>RT</td>
<td>Tensile Resilience</td>
<td>%</td>
</tr>
<tr>
<td>B</td>
<td>Bending rigidity</td>
<td>$10^{-4}$ Nm</td>
</tr>
<tr>
<td>2HB</td>
<td>Bending hysteresis</td>
<td>$10^{-2}$ N</td>
</tr>
<tr>
<td>G</td>
<td>Shear stiffness</td>
<td>N/m deg.</td>
</tr>
<tr>
<td>2HG</td>
<td>Shear hysteresis at 0.5 deg. shear angle</td>
<td>N/m</td>
</tr>
<tr>
<td>2HG5</td>
<td>Shear hysteresis at 5 deg. shear angle</td>
<td>N/m</td>
</tr>
<tr>
<td>LC</td>
<td>Linearity of compression curve</td>
<td>None</td>
</tr>
<tr>
<td>WC</td>
<td>Compressional energy</td>
<td>N/m</td>
</tr>
<tr>
<td>RC</td>
<td>Compressional Resilience</td>
<td>%</td>
</tr>
<tr>
<td>MIU</td>
<td>Coefficient of friction</td>
<td>None</td>
</tr>
<tr>
<td>MMD</td>
<td>Mean deviation of MIU</td>
<td>None</td>
</tr>
<tr>
<td>SMD</td>
<td>Geometrical roughness</td>
<td>µm</td>
</tr>
<tr>
<td>T</td>
<td>Fabric thickness</td>
<td>mm or cm</td>
</tr>
<tr>
<td>W</td>
<td>Fabric weight/Unit area</td>
<td>g/m²</td>
</tr>
</tbody>
</table>
2.17.12 Tensile Property Measurements (KES-FBT)

A fabric sample of 20 cm x 5 cm is clamped to the two jaws of the tensile tester, and is extended up to a pre-set load of 500 N/m; The instrument is based on strip biaxial extension of fabrics. The non-linear tensile behaviour of the fabric is characterised using three parameters such as the tensile energy (WT), the linearity of the load-extension curve (LT) and the tensile resiliency (RT).

2.17.13 Shear Property Measurements (KES - FB1)

In this tester, a shear strain of $8.3 \times 10^{-3}$/s is applied to the fabric up to a maximum shear angle of 8 degrees. The slope of the shear curve is a measure of the shear rigidity. The shear hysteresis and the rigidity values are measured using the KES - FB1 shear tester.

2.17.14 Bending Property Measurements (KES - FB2)

The instrument is based on the pure bending of fabric over an arc of a circle. The fabric of 1 cm in length is subjected to a pure bending at constant curvature of $5 \times 10^{-3}$ m$^{-1}$/s. The bending hysteresis and the rigidity values are obtained from the bending tester. The slope of the curve is a measure of the bending rigidity of fabrics.

2.17.15 Compression Property Measurements (KES - FB3)

The KES - FB3 is used for obtaining the compression parameters. The fabric specimen is compressed at a maximum pressure of 50 g/cm$^2$ in a constant velocity of 20 μm/s. Three different compression parameters such as the compressional energy (WC) the compressive resilience (RC) and the linearity of the compression curve (LC), are used to characterise the compressional properties.
2.17.16 Surface Property Measurements (KES-FB4)

A friction sensor which consists of 10 parallel piano wires of 0.5 nm in diameter is used to measure the friction of fabrics at a normal load of 50 gf. The surface tester also measures the geometrical roughness of fabrics. The surface roughness sensor is a bent piano wire of 0.5 mm diameter. The surface properties are characterised using three parameters. They are:

- **MIU**: Mean frictional coefficient
- **MMD**: Mean deviation of the frictional coefficient
- **SMD**: Mean deviation of surface contour.

The sixteen different mechanical properties measured by the KES-FB system are used to calculate the primary handle values and the total hand value of fabrics.

2.18 FAST SYSTEM

Fabric assurance by simple testing is a simplified system of objective measurement of fabric properties. This system was developed by the Division of Wool Technology, CSIRO, Australia (1989). It is used for assessing appearance, handle and performance of fabrics. FAST consists of three instruments and a test method. Initially, their system was used for determining the handle of woollen and worsted fabrics.

- FAST-1 Compression meter
- FAST-2 Bending meter
- FAST-3 Extension meter
- FAST-4 Dimensional stability test.
2.18.1 FAST-1: Compression Meter

The instrument measures the thickness of fabrics under two predetermined loads. The instrument has a compression cup of 10 cm² in area which provides the initial load of 2 g/cm² on the sample. A maximum pressure of 50 gf/cm² is applied on the sample by an additional weight. The difference in thickness at two different loads is measured as the surface layer thickness.

2.18.2 FAST-2: Bending Meter

This instrument works on a cantilever bending principle. The photo cell in the instrument measures the edge of the bending fabric. The bending length values are read directly and from these values, the bending rigidity values are calculated. Bending rigidity is a measure of the stiffness and the handle of fabrics.

2.18.3 FAST-3: Extensibility Meter

The extensibility of a fabric is a measure of stretch of a fabric which influences the performance and appearance of garments. The extensibility meter measures the extension of fabrics at three different stress levels, 5, 20, and 100 gf/cm simulating the kind of deformations the fabric undergoes during garment manufacture.

2.18.4 FAST-4: Dimensional Stability Test

This is a test method for measuring fabric dimensional stability in terms of its hygral expansion, relaxation and shrinkage. The fabric is dried in an oven at 105°C and the dry dimensions of the fabric are measured. The fabric is then wetted and its wet dimensions are measured. The fabric is then dried and its final dry dimensions are measured. The wet and dry
dimensions are used to calculate the shrinkage and hygral expansions. All the instruments are connected to a PC, and the data are collected and printed out using an in-built software.

Table 2.6 gives the mechanical parameters measured by the FAST system. The results are displayed in the form of "fabric finger prints". These may be used for fabric specifications, developing new fabrics, comparing fabric finishing assessing stability of finished fabrics and predicting tailoring performance and appearance of garments. A typical fabric finger print is shown in Fig.2.14.

Table 2.6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface thickness</td>
<td>ST = T2 - T100</td>
<td>T2 = Average thickness at 2 gf/cm²</td>
<td>mm</td>
</tr>
<tr>
<td>Relaxed surface thickness</td>
<td>STR - T2R - T100R</td>
<td>T2R = Average relaxed thickness at 2 gf/cm²</td>
<td></td>
</tr>
<tr>
<td>Bending rigidity</td>
<td>9.81 x 10⁻⁶ x WC²</td>
<td>W = fabric weight (g/m²) C = bending µN.m length (mm)</td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td>E5</td>
<td>E5 = Average extension at 5 gf/cm.</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>E20</td>
<td>E20 = Average extension at 20 gf/cm</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>E100</td>
<td>E100 = Average extension at 100 gf/cm</td>
<td>%</td>
</tr>
<tr>
<td>Shear rigidity</td>
<td>G = 123/EB5</td>
<td>EB5 = Average bias extension at 5 gf/cm</td>
<td>N/m</td>
</tr>
<tr>
<td>Relaxation shrinkage</td>
<td>RS = (L₁-L₂)/L₁</td>
<td>L₁ = Initial dry length of fabric sample L₂ = Relaxed dry length of fabric sample.</td>
<td>%</td>
</tr>
<tr>
<td>Hygral expansion</td>
<td>HE = (L₂-L₃)/L₁</td>
<td>L₂ = Relaxed wet length of fabric sample</td>
<td>%</td>
</tr>
<tr>
<td>Formability</td>
<td>F = (E₂₀-E₅)/14.7</td>
<td></td>
<td>mm²</td>
</tr>
</tbody>
</table>
Figure 2.14  Fast Control Chart.
Other than these two well established fabric evaluation methods, many research workers have used the Instron tensile tester to measure the handle of fabrics. Force-displacement curves from Instron have been used to characterise fabrics when a circular specimen of fabric was extracted through a nozzle. Sheta (1979) studied the handle of fabrics using the nozzle extraction method. She also carried out a theoretical analysis of the deformation of fabrics at several stages as it is being extracted through the nozzle. Pan and Yen (1992) have also carried out experiments using nozzle extraction method to study the handle of fabrics. They have also analysed the shape of extraction curves. Figure 2.15 shows the typical traces of force-displacement curves as the fabric is being pulled through the nozzle.

Behery (1986) has used the extraction method to calculate the hand moduli for a set of commercial fabrics. He also carried out a correlation study between the total hand value calculated by the Kawabata Evaluation system and hand moduli calculated by the nozzle extraction method. Sultan et al. (1992) used the nozzle extraction method to study the handle of commercial fabrics. They found that the correlation between the nozzle extraction force and the Kawabata measurements was good.

2.19 MECHANICS OF THE SINGLE JERSEY WEFT KNITTING PROCESS

Ghosh and Banerjee (1990) have dealt with the role of the dynamic geometry of the knitting zone and the dynamic forces on the needle hook, as well as importance of cast-off loops hanging around the yarn, pulled in by needles inside knitting zone on the loop formation process. Aisika (1971) has carried out work on mathematical consideration of weft knitting process. Henshaw (1968), Knapton (1968), Knapton and Munden (1966ab) and Peat and Spicer (1973) have contributed to the dynamics of weft knitting and loop formation process. Pietikäinen (1981) and Pietikäinen and Valkama (1983) have contributed to the influence of yarn properties and type of yarn feeding
Figure 2.15 Typical force displacement curve in fabric extraction test.
on loop forming process. Banerjee (1995) gives his views on a single jersey loop formation system. Ghosh's (1988) study on the study of mechanics of single jersey loop formation is also noteworthy. Recently, Banerjee and Ghosh (1999) have formulated a deterministic model of the single jersey loop formation process. A computer program, based on the model of the single jersey loop-formation process, is developed for predicting the effect of some relevant yarn, machine, and process variables on loop length as well as the resulting yarn tension profile inside the knitting zone. The model is validated qualitatively in terms of the loop length and yarn tension-profile inside the knitting zone as well as quantitatively only in terms of the loop length. They caution that a higher feeder density machine, although possesses certain advantages, leads to greater variation in loop length. They feel that very high-quality fabrics can only be produced with yarns that are very smooth, even and strong to be knitted only under conditions satisfying a low variation in loop length.

Ray and Banerjee (2000) have dealt with the simulation of the 1 x 1 rib loop formation process on a dial and cylinder machine on a computer. Various concepts such as geometry of knitting zone, wrap angles, loop arm configuration etc., of the 1 x 1 rib loop formation, which have been developed, are incorporated in the computer programme in order to predict the loop length and yarn tension profile under both synchronised and delayed timings. The length of yarn in each loop and the yarn tension developed inside knitting zone during knitting - the two crucial output variables - have been used for validating the model. The model, besides following a trend similar to that of the real system, is also found to be sensitive and sound enough to permit theoretical investigations into the mechanics of 1 x 1 rib loop formation system.
2.20 SUMMARY

From the foregoing it is clear that a considerable amount of work related to weft-knitted fabrics has been done. What appears to be less emphasised in the literature is the dimensional properties of pique fabrics, and the effect of yarn properties on the low stress mechanical properties of weft-knitted fabrics. Physical properties of pique fabrics such as elastic recovery and handle have also been investigated.