2

Objective measurement technology of woven fabrics

2.1 Significance of Fabric Objective Measurement technology

Fabric Objective Measurement of mechanical, geometrical, surface and large deformation properties represents a very powerful tool for the quality control of fabric manufacturing, finishing and refinishing operations. It presents the possibility of an integrated computerised scientific database incorporating in objective terms the enormous wealth of experience of numerous experts who have worked in the textile and clothing industries over many years in different countries throughout the world. The application of this technology is becoming more crucial due to three important factors:

(1) the increasing level of automation in both textile and clothing manufacture;
(2) the gradual disappearance of personnel with traditional textile knowledge based on many years of experience and the simultaneous emergence within industry of conventionally trained engineers to carry out the production, research, development and quality control functions;
(3) the widespread use of the internet and all kinds of digital communication tools, as well as the large number of product varieties due to shorter terms of seasonal products and the need for quick response to maintain competitiveness in business.

The development of Fabric Objective Measurement of mechanical properties for apparel products originated with Peirce in the 1920s and 1930s (Peirce, 1930, 1937). He investigated the basic equilibrium structure of a plain-weave fabric in terms of force equilibrium and tried to build up the basic theory of fabric mechanics. His work was further developed by a number of other researchers. Grosberg and his co-workers Park and Swani at Leeds University during the 1960s pioneered the theoretical analysis of fabric mechanical properties such as tensile, bending, buckling, shear and compression (Grosberg, 1966; Grosberg and Park, 1966; Grosberg and Swani, 1966).

Their contributions led to a relatively clear picture of the physical and mechanical description of woven fabric and deformation properties.

The Swedish research team headed by Lindberg *et al*. (1960) during the late 1950s and 1960s, extensively studied the mechanical behaviour of fabrics and related the basic mechanical properties of fabric to the tailorability and appearance of manufactured clothing. Their investigations become the focus of serious work by other researchers. Experimental techniques for the measurement of these mechanical properties have been evolved over a number of years by many researchers. A variety of equipment and test methods are now available.

Although much research was aimed at developing Fabric Objective Measurement techniques and various methods for measuring these properties were developed, these techniques were practised only by academics or research institutes. Their widespread use in the textile and clothing industries was still hindered by the unavailability of a coherent system with sophisticated and sensitive instruments for measuring the low-stress mechanical properties of fabrics. In addition, without a standardised testing method, further development and applications of these low-stress mechanical properties in the apparel industry would be limited. A research leader in Fabric Objective Measurement technology was Sueo Kawabata, who developed a testing device called the Kawabata Evaluation System (KES) that, within 10 years, was to become a standard textile test facility around the world. The KES fabric evaluation system is a sophisticated computer testing facility that enables a variety of fabric tests to be carried out (Kawabata, 1982).

The KES system enables accurate and reproducible measurement of fabric low-stress mechanical properties, which facilitates the extensive comparison of experimental findings by apparel engineers and researchers all over the world and efficient communication between various manufacturing sectors, buyers and apparel designers. However, criticisms still exist due to the high cost of the instrument. The system also requires experts for the interpretation of the resulting data. These deficiencies led to the development of another testing device called the FAST (Fabric Assurance by Simple Testing) system by CSIRO in Australia. The FAST system is much cheaper and is becoming more attractive to the industry. Undoubtedly, these developments coincided with an increase in the level of automation which demanded prediction and control of fabric behaviour during production. In this chapter, the development of the principles and instrumentation of both systems will be introduced.

The Virtual Image Display System (VIDS) and more recently the intelligent Fabric Surface Analysis System (FabricEye®) are new objective measurement tools based on image analysis and artificial intelligence technologies, which have been developed specially for the analysis of fabric geometrical and surface properties. The VIDS image system is a two-dimensional image analysis system which combines the video output from a TV camera with the graphics display of the computer so that measurements may be made directly from the TV image, but the general measurement using the VIDS image system still depends on manual mouse clicking and dragging. However, FabricEye® is an automatic three-dimensional image analysis system; it can generate a 3D profile of fabric surface and give specimens an objective grade automatically.

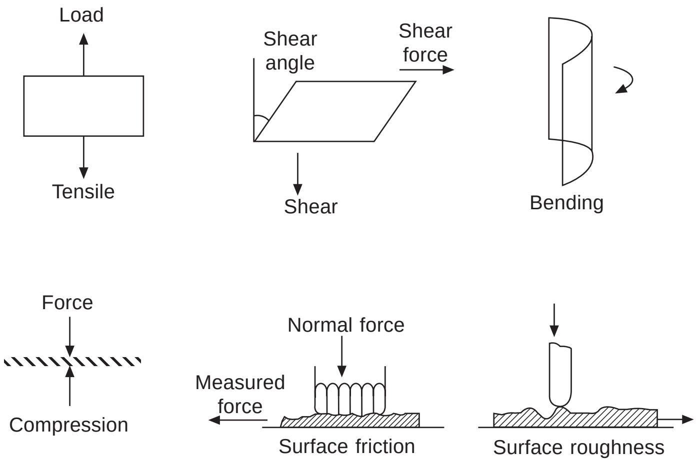
Other objective measurement technologies are also included in this chapter, such as Scanning Electron Microscopy (SEM) for surface effect and cantilever and drapemeter for complex deformation. It seems that the most important consequence of the introduction of fabric objective measurement technology is the promotion of technological communication between various sectors of the textile and clothing industries, research and development workers and all other areas (e.g. fibre production, retailing, merchandising) concerned with fibres, textiles and clothing. Consequently, production control and quality assurance within textile and clothing companies should become much more rational and efficient, leading to products of higher and more consistent quality. In practical terms, the fabric objective data will allow manufacturers to anticipate and overcome problems before they appear. In summary, fabric objective measurement technology provides the key for scientific and engineering as well as production principles:

(1) optimisation of fabric properties to engineer new fabrics of desirable quality and performance attributes for particular end-uses;
(2) development of new finishes, finishing agents and finishing machinery for textile materials;
(3) control of fabric finishing/refinishing to meet fabric mechanical, surface and dimensional property goals;
(4) fabric specification and process control for clothing manufacture;
(5) total fabric development from raw material to tailored garments.

2.2 Mechanical properties measurement

2.2.1 The KES system

The KES system is the first advanced and unique solution to the problem of user-friendly testing of fabric mechanical properties, and it has acquired great popularity in many countries due to the high precision and reproducibility in measurement which it offers. With the information provided by this system, it is possible to achieve effective communications and cooperation among the various sectors (e.g. researchers, industry sectors and traders) of the textile and clothing industries by specifying performance requirements and transactions based on fabric properties data. Generally speaking, the KES system has the following features:



2.1 Measuring principles of the KES system.

(1) The testing is very comprehensive. Five charts and 16 parameters in the warp and weft directions can be obtained in one system, which covers almost all aspects of the physical properties of a fabric, in contrast to those testers which test single deformation modes.
(2) The tested strain regions are very similar to what happens when the fabrics are handled or when they are spread, cut, fused, sewn, or shaped and worn.
(3) A sample of the same size (20 cm × 20 cm) can be tested through the whole system. Particularly, the size of samples used for tensile testing is different from the conventional large length/width ratio such as is used on the Instron® machine.
(4) It is highly automated, and results from testing can be shown accurately on the computer attached to it, with charts and printouts of property parameters.

Detailed information on the KES instruments and the principles of measurement as shown in Fig. 2.1 can be found in KES manuals (1–4).

2.2.1.1 Configuration of the KES system

In practical terms, the extension or stress applied to woven fabrics during manufacturing, finishing, garment construction and wear is generally within the low-stress region of their characteristic stress–strain behaviour. The major stresses involved in fabric deformation under low-stress conditions are tensile, shear, bending and compression, and the KES system is a device capable of realising the testing of these low-stress deformations. It consists of four precision instruments originally designed to measure key mechanical properties related to the hand, drape and formability of fabrics, as shown in Table 2.1.

Table 2.1 The properties measured on the KES-F system

Instrument	**Properties measured**
KES-FB1	Tensile and shear
KES-FB2	Pure bending
KES-FB3	Compression
KES-FB4	Surface characteristics, i.e. fabric surface profile and coefficient of friction

KES-FB1 Tensile and shear tester

Just as the title suggests, this tester is for tensile and shear properties. With this tester, the tensile indices like extensibility and tensile rigidity can be obtained simply by applying a tensile strain to a sample held by two chucks. In the determination of shear property, the sample will be subjected to a preset shear deformation of ±8° shear angle under a constant tensile force.

KES-FB2 Pure bending tester

This instrument uses the principle of pure bending whereby a fabric sample is bent in an arc of constant curvature which is changed continuously. The minute bending moment of the sample is detected and the relationship between the bending moment and the curvature is recorded on an X-Y recorder.

KES-FB3 Compression tester

The instrument is designed to measure the fabric lateral compressional deformation properties which are important in the assessment of fabric handle. In the compression testing, a standard area of the fabric is subjected to a known compressive load and then the load is gradually relieved. The load is applied through a movable plunger that moves up and down and compresses the fabric on a stationary platform. Fabric compressibility can be obtained by calculating the percentage reduction in fabric thickness resulting from an increase in lateral pressure (from 50 Pa to 5 kPa). Moreover, the relationship between compressional strain and stress is automatically recorded on an X-Y recorder or computer linked with the tester.

KES-FB4 Surface tester

The instrument measures fabric surface properties which are closely related to hand feel of fabrics. The fabric frictional coefficient and the mean deviation of the coefficient of friction are detected by the friction contactor, which is directly connected to a frictional force transducer. Geometrical surface roughness is detected by the contactor for roughness. All of the measured parameters can be obtained directly from the calculation circuit of the instrument.

2.2.1.2 Information obtained from the KES-F system

A total of 16 parameters can be obtained from this system. These are:

Tensile parameters
EMT – percentage tensile elongation which is the ratio of actual extension to the original sample length, expressed as a percentage;
WT – tensile energy or work done in tensile deformation represented by area under the stress–strain curve;
RT – tensile resilience which is the ratio of work recovered to work done in tensile deformation, expressed as a percentage;
LT – tensile linearity which is a measure that defines the extent of non-linearity of the stress–strain curves. *LT* value below 1.0 indicates that the stress–strain curve rises below a 45° straight line while *LT* values greater than 1.0 indicate that the stress–strain curve falls above a 45° straight line.

Shear parameters
G – shear modulus which is the slope of the shear curve that falls between shear angles 0.5° and 5°;
2*HG* and 2*HG*5 – hysteresis width at shear angle 0.5° and 5°, respectively.

Bending parameters
B – bending stiffness which is the slope of the bending curve that lies between the radius of curvature of 0.5 cm^{-1} and 1.5 cm^{-1};
2*HB* – hysteresis width at a bending curvature of 0.1 cm^{-1}.

Compressional parameters
T_0 – fabric thickness (mm) at a very low compressive stress of 0.5 gf/cm^2;
T_m – fabric thickness (mm) at a maximum compressive stress of 50 gf/cm^2;
WC – compressional energy or work done in compression represented by the area under the compressive curve;
RC – compressive resilience which is the work recovered to the work done in compression deformation, expressed as a percentage;
LC – compression linearity which is a measure of the deviation of the deformation curve from a straight line. Higher values of *LC* imply a higher initial resistance to compression. In general, all fabrics have low values for linearity compared with tensile testing. Values range from 0.25–0.36.

Table 2.2 The parameters measured on the KES-F system

Property	Symbol	Parameter measured	Unit
Tensile	*EMT*	Extensibility, the strain at 500 gf/cm	[%]
	LT	Linearity of tensile load–extension curve	[–]
	WT	Tensile energy per unit area	[gf·cm/cm^2]
	RT	Tensile resilience, the ability of recovering from tensile deformation	[%]
Bend	*B*	Bending rigidity, the average slope of the linear regions of the bending hysteresis curve to ± 1.5 cm^{-1} curvature	[gf·cm^2/cm]
	2*HB*	Bending hysteresis, the average width of the bending hysteresis loop at ± 0.5 cm^{-1} curvature	[gf·cm/cm]
Shear	*G*	Shear rigidity, the average slope of the linear region of the shear hysteresis curve to ± 2.5° shear angle	[gf/cm·degree]
	2*HG* &	Shearing hysteresis, the average widths of the shear hysteresis loop at ± 0.5° shear angle	[gf/cm]
	2*HG*5	Shearing hysteresis, the average widths of the shear hysteresis loop at ±5° shear angle	[gf/cm]
Surface	*MIU*	Coefficient of fabric surface friction	[–]
	MMD	Mean deviation of *MIU*	[–]
	SMD	Geometrical roughness	[mm]
Compression	*LC*	Linearity of compression-thickness curve	[–]
	WC	Compressional energy per unit area	[gf·cm/cm^2]
	RC	Compressional resilience, the ability of recovering from compressional deformation	[%]
Thickness	*T*	Fabric thickness at 50 N/m^2	[mm]
Weight	*W*	Fabric weight per unit area	[mg/cm^2]

Surface parameters

MIU	– coefficient of surface friction as measured over 3 cm length of fabric;
MMD	– mean deviation of coefficient of friction;
SMD	– surface roughness (mean deviation of surface peaks representing thick and thin places).

All mechanical properties measured on the KES system are summarised in Table 2.2.

2.2.2 The FAST system

FAST is a set of instruments and test methods developed by the CSIRO Division of Wool Technology (Australia) for measuring those properties which affect the tailoring performance of the fabric and the appearance of the garment in wear. It consists of three simple instruments and a test method, requiring a specific sample size for both the instrumental tests and the dimensional stability test. In practice, about half a metre of fabric at full width is adequate to carry out the full range of tests.

FAST was developed to provide the industry with a simple, robust and relatively inexpensive system for the objective measurement of those fabric properties important in garment manufacture; it is thus mainly used by fabric manufacturers, finishers and garment makers. However, FAST has potential applications at all stages of fabric manufacture and use. As a result of these wide ranging applications another of the objectives of FAST can be achieved. This is to provide a language with which garment makers and fabric producers can communicate about cloth and garment properties and performance.

2.2.2.1 Configuration of the FAST system

The system comprises three simple instruments and a test method, listed as in Table 2.3.

To ensure error-free calculations, the system is connected to a computer where measurements are recorded directly and displayed on the monitor.

FAST-1 Compression meter

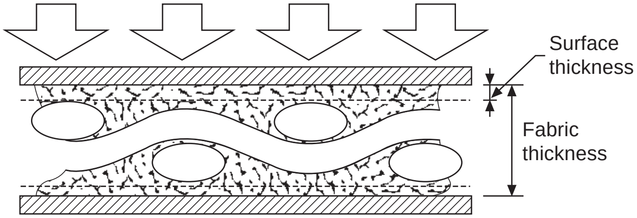
FAST-1 is a compression meter which can enable the measurement of fabric thickness and surface thickness at two predetermined loads. Surface thickness is defined as the difference between the values of thickness at the two predetermined loads of 0.2 kPa and 10 kPa. The measurement principle is shown in Fig. 2.2. The pressure at which thickness is measured is controlled by adding weights to the measuring cup.

FAST-2 Bending meter

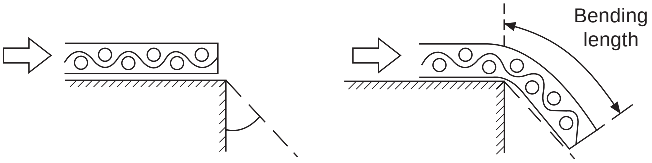
FAST-2 is a bending meter which measures the bending length of the fabric. From this measurement the bending rigidity of the fabric may be calculated. The instrument uses the cantilever bending principle described in British Standard method (BS: 3356 (1990)). However, in FAST-2 the edge of the fabric is detected using a photocell, and not by eye as in some other test

Table 2.3 Configuration of the FAST system

Instrument	**Properties measured**
FAST-1	Compression
FAST-2	Bending
FAST-3	Extension
FAST-4 (test method)	Dimensional stability



2.2 Measuring principle of the FAST-1 compression meter.

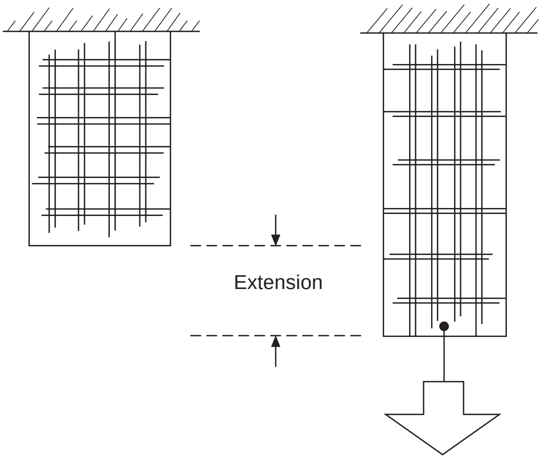


2.3 Measuring principle of the FAST-2 bending meter.

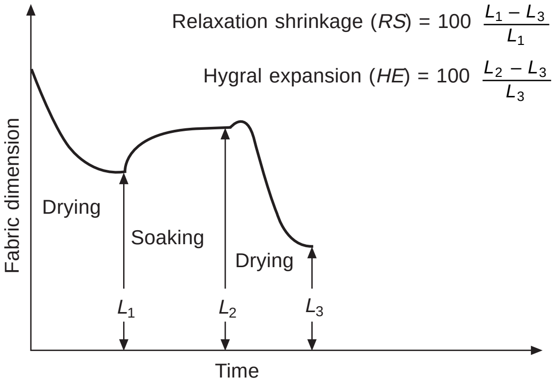
instruments. As well as making the instrument simpler to use, the elimination of this source of operator error makes FAST-2 more accurate than alternative instruments. The values of the bending length are read directly from a display on the instrument. Figure 2.3 gives the measuring principle.

FAST-3 Extension meter

FAST-3 is an extension meter which operates on a simple lever principle as shown in Fig. 2.4. By removing weights from the counterbalancing beam, the extensibility of the fabric can be measured at three different loads, thereby simulating the kind of deformation the fabric is likely to undergo during



2.4 Measuring principle of the FAST-3 extension meter.



2.5 Measuring principle of the FAST-4 bending meter.

garment manufacture. The extensibility of the fabric can, in theory, be measured at any angle to the warp (or weft) threads. In practice, it is normal to measure the extensibility in only the warp, weft and bias directions.

FAST-4 Dimensional stability test

The final component of FAST is a test method which measures the changes in the dimensions of fabrics that occur when the fabric is exposed to changing environmental conditions. The test is a modification of the conventional wet–dry test. The FAST-4 test can be completed in less than two hours and does not require a conditioned atmosphere. A schematic diagram of the test procedure is shown in Fig. 2.5.

2.2.2.2 Information obtained from the FAST system

Using the FAST system, 14 parameters can be measured or calculated; these are listed in Table 2.4. The measured parameters are plotted on a control chart from which a good prediction of the performance of the fabric during garment manufacture can be derived. The importance of these parameters varies according to the end use of the fabric being tested. The system provides simple but reliable and quick response information for the control of fabric finishing and tailoring. The following section provides a detailed explanation of the properties measured by the FAST system.

Dimensional stability (FAST-4)

This term is used to describe the change in the dimensions of fabrics that occurs when the fabric is exposed to changing environmental conditions. For wool and wool-containing fabrics, there are two important components of dimensional stability.

Table 2.4 The parameters measured on the FAST system

Property	**Symbol**	**Parameter measured**	**Unit**
Tensile	$E5$	Extension at 5 N/m	[%]
	$E20$	Extension at 20 N/m	[%]
	$E100$	Extension at 100 N/m	[%]
	$EB5$	Bias extension	[%]
Bending	C	Bending length	[mm]
	B	Bending rigidity	[μN·m]
Shear	G	Shear rigidity	[N/m]
Compression	$T2$	Thickness at 2 gf/cm^2	[mm]
	$T100$	Thickness at 100 gf/cm^2	[mm]
	ST	Surface thickness	[mm]
	STR	Released surface thickness	[mm]
Dimensional stability	RS	Relaxation shrinkage	[%]
	RC	Hygral expansion	[%]
Derived parameter	F	Formability	%·mm^2

Relaxation shrinkage

The irreversible change in fabric dimensions (shrinkage or expansion) that occurs when the fabric is wet out or exposed to steam. Relaxation shrinkage is caused by the release of cohesively- or temporarily-set strains which are imposed on fabrics during the late stages of finishing. In the FAST system, relaxation shrinkage is defined as the percentage change in dry dimensions of the fabric measured after relaxation in water at room temperature.

Hygral expansion

Hygral expansion is the reversible change in the dimensions of the fabric that occurs when the moisture content of the wool fibres is altered. Using FAST, hygral expansion is defined as the percentage change in dimensions of the relaxed fabric from wet to dry. These two components are described mathematically as follows:

$$\text{Relaxation shrinkage} = \frac{L_1 - L_3}{L_1}$$

$$\text{Hygral expansion} = \frac{L_2 - L_3}{L_3}$$

where L_1 = length of dry, relaxed fabric, L_2 = length of wet fabric after relaxation in water and L_3 = length of dry, unrelaxed fabric.

Other measures of relaxation shrinkage are available such as the WIRA$^{\text{TM}}$ steam cylinder or open press shrinkage test. These correlate well with the FAST wet–dry method.

Other methods of measuring dimensional stability are also available, and these include the DIN test, the HESC test and locked press shrinkage. However, these tests do not separate the two components of dimensional stability and can give misleading results on some fabrics.

Extensibility (FAST-3)

The extensibility of a fabric measures the increase in fabric dimensions which occurs when it is subjected to an applied load. Using the FAST system, extensibility is measured as a percentage increase in length at sample loadings of 5 gf/cm, 20 gf/cm and 100 gf/cm width (98.1 N/m). The quoted value for fabric extensibility is that measured at 100 gf/cm. The extensibilities in the warp and weft directions measured at 5 gf/cm and 20 gf/cm are used to calculate fabric formability. Bias extensibility is measured only at 5 gf/cm width.

Bending rigidity (FAST-2)

The bending rigidity of a fabric is defined as the couple required to bend that fabric to unit curvature. The FAST system determines bending rigidity from the cantilever bending length of the fabric, measured using the principle described in BS: 3356 (1990), and fabric weight. Bending rigidity is given by:

$$\text{Weight} \times (\text{Bending length})^3 \times 9.807 \times 10^{-6}$$

with bending rigidity in μN·m, bending length in mm and fabric weight in g/m^2.

Shear rigidity (FAST-3)

Shear deformation of a fabric can be described as a trellising motion in which the angle between warp and weft threads is changed (from 90°) without imposing an extension on either set of threads. The shear rigidity of a fabric is a measure of the force required to deform the fabric in shear. In the FAST system, shear rigidity is calculated from the bias extensibility of the fabric under a load of 5 gf/cm and is given by:

$$\frac{123}{\text{Bias extensibility}}$$

with shear rigidity in N/m and bias extensibility in %.

Thickness/surface thickness (FAST-1)

Using the FAST system, the thickness of the fabric is measured at 2 gf/cm^2. The thickness of the fabric is also measured at 100 gf/cm^2 and the surface thickness, defined as the difference between the thicknesses at the two loads, is calculated from the measured data:

$$\text{Surface thickness} = \text{Thickness (2)} - \text{Thickness (100)}$$

Relaxed thickness/surface thickness (FAST-1)
The relaxed thickness and surface thickness of the fabric are measured after the fabric has been relaxed in steam (open press for 30 sec) or water (at 20 °C for 30 min). Naturally the samples must be reconditioned to the standard atmosphere before the fabric is retested using FAST-1.

Formability
The FAST system uses the derived parameter, formability, in the analysis of fabrics. Formability is a measure of the extent to which a fabric can be compressed in its own plane before it will buckle. This parameter, as the product of the bending rigidity and the extensibility of the fabric at low loads, is defined in the FAST system as:

$$\text{Formability} = \text{Bending rigidity} \times \frac{\text{Extension (20)} - \text{Extension (5)}}{14.7}$$

with formability in mm^2, bending rigidity in $\mu N \cdot m$ and extension in %.

2.2.3 Comparison of the two measuring systems

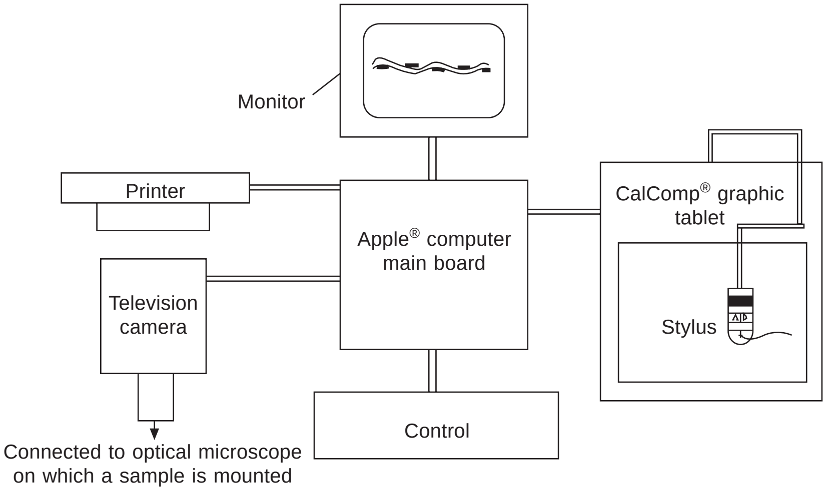
Both the KES-F and the FAST systems were originally designed for measuring low-stress mechanical properties in an accurate and reproducible manner, but they differ in several ways. First, the FAST system uses standard fabric strips 5 cm long whereas the KES system uses 20 cm × 20 cm strips. Second, the two systems also adopt different testing principles: the KES set of instruments measures the entire deformation-recovery behaviour while the FAST system determines the amounts of deformation to a single point on the deformation curve (Ly *et al.*, 1988). For example, the KES bending tester employs the principle of pure bending in measuring the bending property. The constantly changing curvatures of the fabric specimen are recorded allowing both elastic and frictional components for the bending moment to be measured separately. The FAST bending tester, on the other hand, is based on the cantilever principle. In the case of measuring the shear property, the principle of bias extension measurement is adopted by the FAST shear tester whereas the KES-F system measures the simple shear with sides at constant length.

A number of workers also compared the results measured by both systems. Ly *et al.* (1991) found the results measured by the two systems to be highly correlated with each other, even though significant difference in values may exist between them. The approach used in the KES system seems more similar to the actual fabric deformation in shearing and bending and it allows continuous measurement of deformations. In addition, the shape of the load–extension curve, which can reveal the actual deformation characteristics of fabrics more clearly and accurately, is attainable. On the one hand the FAST system is simpler to use and cheaper. The price of the FAST system is only about one eighth of the price for the KES-F system. Therefore, the FAST system can be more easily applied in industry. On the other hand, for more in-depth research and development work on the low-stress mechanical properties of fabrics, the KES system is preferred. Therefore, the general opinion was that FAST data could be swiftly applied to commercial production, but the KES system was said to be an ideal laboratory tool and a precise factory testing facility.

2.3 Geometrical and surface properties measurement

2.3.1 The VIDS image analysis system

Most of the geometrical parameters can be measured by the VIDS image analyser (manual for VID system). Figure 2.6 is a systematic diagram of the VIDS image analysis system. The VIDS system combines the video output from a TV camera with the graphics display of an Apple® computer so that measurements may be made directly from the TV image. A CalComp® digitising tablet allows the operator to ensure a range of feature parameters using VIDS software packages. VIDS software packages contain general measurement, area fractions measurement, four-dot measurement, two-dot measurement, linear measurement, twist angle and point count programs. The results of these measurements may be displayed on the computer screen, printed using a printer or stored on floppy disk.



2.6 Schematic illustration of the image analysis system.

The VIDS general measurement program allows the user to draw round features displayed on the computer screen using the digitising tablet and four-button cursor. The following results may be obtained for each feature as well as the mean and the standard deviation of each:

- Area, perimeter, form factor, maximum projected horizontal and vertical lengths. This program was used to measure area of yarn cross-section and crimp height of yarns in the present case.
- The VIDS Two-Dot measurement program allows the rapid measurement of features which can be defined by two points. This program was used for measuring major and minor diameters of yarns in a fabric.
- The twist angle program allows the user to measure the angle of a feature to the horizontal line. It was employed to measure the weave angle of warp and weft yarns in a fabric.

2.3.1.1 Preparation of samples

In examining fabric structure, it is first necessary to set the fabric in resin. This is done by cutting a small piece of fabric such that its length and width are 25 × 25 mm, and sticking this sample on a stiff paper frame with a square hole of about 20 × 20 mm in the middle. The stiff paper with the sample fabric is inserted vertically into a rubber mould. A liquid mixture of epoxy resin ARALDITE MY753 and ARALDITE HARDENER HY951 (ratio 10:1) is poured into a mould. After 24 hours, the resin block is cut into very thin slices on a slow speed saw. The thickness of a slice is usually larger than Å (major diameter of thread values of 1 and 2 for warp and weft). So it is about 100–300 microns in the case of fabrics used in the present investigation. Transparent embedding agents are commercially available. The slices are then employed for the observation and measurement of various geometrical parameters and SEM.

To prepare good samples, care should be taken with the following problems:

- The solution ratio of the mixture liquid must not be less than 1:10. If it is, the sample block containing the fabric will be too soft. When cutting, it may cause distortion of the yarns in the fabric, producing incorrect data.
- Drying time of less than 24 hours or a holding force of the sample for cutting which is too large could cause the same problem.
- The thickness of a slice also must be appropriate. If the slice of a sample is too thick, the adjacent yarns may not be separated from each other; if it is too thin, the yarn may be cut into pieces.

All of these affect the measurability of a sample.

2.3.1.2 Measurement of geometrical parameters

Sett, thread-spacing

The number of warp and weft threads per centimetre was determined by using parallel-line gratings as described in British Standard BS 2862: 1984. Five readings of every sample were taken to represent the threads per unit length of one material. The average number of threads per cm and the thread-spacing were then calculated. If *n* stands for the threads per unit length, the spacing *p* can be calculated using the following formula

$$p_i = \frac{1}{n_j} \qquad i, j = 1\text{–}2 \qquad [2.1]$$

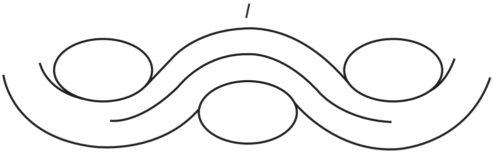
The tested sett and thread-spacing are listed in Table 2.5.

Yarn crimp

Two methods, namely the image analysis method and the tension method, were used for yarn crimp in a woven fabric.

Table 2.5 Sett and space of sample fabrics

Sample	Sett (threads/cm)		Space (mm)	
	n_1	n_2	p_1	p_2
2	58.7	28.7	0.170	0.348
3	52.8	26.8	0.189	0.373
4	57.9	27.6	0.173	0.362
5	59.5	29.5	0.168	0.339
6	52	27.2	0.192	0.368
7	66.9	34.7	0.149	0.288
9	67.7	33.5	0.148	0.299
10	72.84	37.4	0.137	0.267
11	72.84	37.4	0.137	0.267
12	71.7	37.4	0.139	0.267
13	59	28.7	0.169	0.348
14	59	29	0.169	0.345
16	19.69	13.39	0.508	0.747
18	19.69	13.39	0.508	0.747
20	21.65	13.19	0.462	0.758
21	22.64	20.08	0.442	0.498
22	23.23	16.54	0.431	0.605
23	36.22	26.77	0.276	0.374
24	28.35	20.87	0.353	0.479
25	24.8	21.65	0.403	0.462
26	31.1	21.85	0.323	0.458
27	28.74	25.98	0.348	0.385
1	51.2	41.7	0.195	0.24
8	37.8	33.86	0.265	0.295



2.7 Measurement of yarn.

Tested by image analysis

The determination of 1, the yarn length per unit, is a key parameter for crimp calculation. The image of the cross-section of a yarn in a fabric is displayed on the computer screen through a magnified system. The length of the central line of a yarn was measured using the linear measurement program of a VIDS system as shown in Fig. 2.7. Then, the crimp C is calculated as equation (2.2).

$$c_i = \frac{1 - p_j}{p_j} \times 100\% \quad i, j = 1\text{–}2 \tag{2.2}$$

Tested by tension method

Yarn crimp was also measured by applying a specified tension to a length of yarn and measuring the resultant extension, which may be dependent on the particular tension used in testing. The testing method referred to British Standard BS 2862: 1984.

The tested data for every fabric using these two methods are listed in Tables 2.6 and Table 2.7.

Crimp height

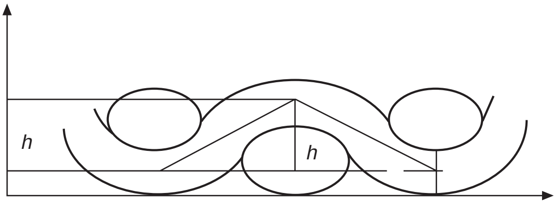
As shown in Fig. 2.8, the crimp height of yarns was measured using the general measurement program introduced above. The sample is positioned

Table 2.6 Measured crimp using image method

Sample	c_1	c_2	**Sample**	c_1	c_2
2	11.93	23.27	16	15.15	6.33
3	9.88	16.16	18	4.44	14.20
4	13.16	14.18	20	18.25	19.07
5	18.00	19.00	21	16.46	15.46
6	14.24	24.80	22	0.89	16.15
7	14.51	20.42	23	20.47	19.53
9	17.25	15.09	24	6.44	21.91
10	12.20	16.54	25	6.08	4.16
11	12.20	16.54	26	11.44	8.85
12	15.94	14.72	27	6.52	9.21
13	11.93	18.00	1	12.59	22.88
14	18.90	12.00	8	15.12	9.62

Table 2.7 Measured crimp using tension method

Sample	c_1	c_2	Sample	c_1	c_2
2	9.19	6.27	16	4.36	6.06
3	8.91	5.93	18	6.64	7.86
4	8.43	5.36	20	1.82	18.57
5	9.29	5.50	21	2.21	9.43
6	7.14	3.64	22	3.15	6.43
7	9.75	6.21	23	4.25	14.38
9	9.56	5.16	24	2.86	4.30
10	7.31	4.50	25	4.30	6.79
11	8.41	5.56	26	3.57	8.14
12	8.21	4.00	27	4.14	10.55
13	7.86	5.04	1	6.36	11.44
14	9.79	5.75	8	11.00	16.89



2.8 Measurement of crimp height.

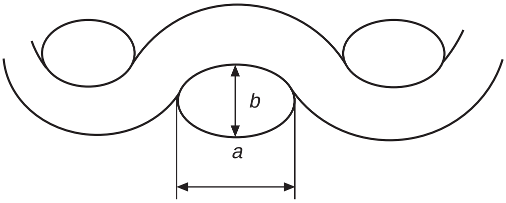
to ensure that the surface of the fabric touches the horizontal line. In order to do this, peaks of the weave of the tested fabric are positioned on the horizontal line. We need only spot three places to form a close triangle. The height of the triangle is read by the maximum vertical projected length, which is the crimp height of a yarn within the fabric. The measured results are listed in Table 2.8.

Table 2.8 Measured crimp heights

Sample	h_1 (mm)	h_2 (mm)	Sample	h_1 (mm)	h_2 (mm)
2	0.144	0.081	16	0.193	0.181
3	0.144	0.089	18	0.111	0.22
4	0.154	0.086	20	0.153	0.328
5	0.151	0.079	21	0.164	0.217
6	0.167	0.082	22	0.145	0.195
7	0.15	0.068	23	0.147	0.153
8	0.131	0.074	24	0.164	0.244
10	0.118	0.061	25	0.136	0.129
11	0.107	0.064	26	0.129	0.122
12	0.106	0.064	27	0.134	0.13
13	0.134	0.07	1	0.103	0.098
14	0.159	0.081	8	0.084	0.134

Yarn diameters

Minor and major diameters of yarns, as shown in Fig. 2.9, were measured using the two-dot program. The measurements are made by positioning the screen cursor over the first point to be marked and pressing down a button on the cursor so that a dot appears on the screen in the middle of the cursor. The button on the cursor is then lifted, moved and pressed down again to give a second dot and also a beep which indicates that a complete two-dot measurement has been made. The tested minor and major diameters and flattening coefficients are shown in Table 2.9.



2.9 Measurement of yarn diameters in fabric.

Table 2.9 Measured diameters for samples

Sample	**Major diameters**		**Minor diameter**		**Flatten coeff.**	
	a_1	a_2	b_1	b_2	e_1	e_2
2	0.21	0.24	0.08	0.1	2.63	2.4
3	0.18	0.2	0.09	0.1	2	2
4	0.17	0.19	0.09	0.09	1.89	2.11
5	0.21	0.21	0.08	0.09	2.63	2.33
6	0.22	0.23	0.1	0.09	2.2	2.56
7	0.2	0.18	0.07	0.07	2.86	2.57
9	0.21	0.18	0.07	0.09	2	1.86
10	0.19	0.15	0.06	0.06	3	2
11	0.16	0.16	0.06	0.06	3.17	2.5
12	0.15	0.16	0.06	0.06	2.67	2.67
13	0.19	0.21	0.08	0.09	2.5	2.67
14	0.2	0.2	0.08	0.09	2.38	2.33
16	0.19	0.2	0.13	0.14	1.46	1.43
18	0.29	0.31	0.25	0.21	1.16	1.48
20	0.3	0.45	0.22	0.19	1.36	2.37
21	0.25	0.31	0.17	0.15	1.47	2.07
22	0.18	0.29	0.15	0.12	1.2	2.42
23	0.2	0.25	0.14	0.12	1.43	2.08
24	0.22	0.27	0.12	0.14	1.83	1.93
25	0.32	0.32	0.11	0.12	2.91	2.67
26	0.21	0.3	0.13	0.1	1.62	3
27	0.23	0.27	0.09	0.09	2.56	3
1	0.16	0.18	0.09	0.08	1.78	2.25
8	0.16	0.13	0.08	0.07	2	2.4

Table 2.10 Measured and calculated areas of yarns

Sample	**Calculated**	**Measured**		
	$A_1 = A_2 = A$	A_1	A_2	A_1/A_2
2	0.013	0.01419	0.01717	0.826
3	0.01306	0.012	0.01445	0.830
4	0.01306	0.01236	0.01517	0.815
5	0.01306	0.01395	0.01441	0.968
6	0.01628	0.01463	0.01487	0.984
7	0.01093	0.01111	0.01113	0.998
9	0.01093	0.01087	0.01474	0.737
10	0.00817	0.0084	0.00922	0.911
11	0.00818	0.0784	0.0791	0.991
12	0.00817	0.00878	0.0096	0.915
13	0.01306	0.0125	0.01406	0.889
14	0.01306	0.01434	0.01542	0.930
16	0.01628	0.0178	0.02013	0.884
18	0.0543	0.06393	0.06479	0.987
20	0.04635	0.05177	0.07174	0.722
21	0.0543	0.02719	0.04157	0.654
22	0.02163	0.02099	0.03355	0.626
23	0.02163	0.01589	0.0201	0.791
24	0.03109	0.02644	0.03355	0.788
25	0.02716	0.0229	0.02846	0.805
26	0.01862	0.01919	0.02095	0.916
27	0.02163	0.01591	0.01847	0.861
1	0.01093	0.01005	0.01038	0.968
8	0.01649	0.0078	0.01009	0.773

Area of yarn cross-section in a fabric

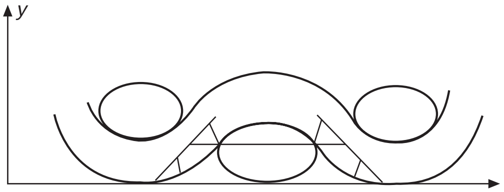
To measure the area of yarn cross-section, one draws round the border of the cross-section of a yarn using the general measurement program. When the beginning and the end of the borderline are overlapped, the complete measurement of area of a yarn has been made. The measured and calculated areas from calculated diameters are listed in Table 2.10.

Weave angle

The twist-angle program in the VIDS system was used for testing the weave angle of yarns in a fabric as shown in Fig. 2.10. The line formed by connecting two dots which are on the central line of the yarn has an angle with the horizontal line. This is weave angle θ. The measured results are listed in Table 2.11.

The cross-section photographs shown in this chapter were taken using a camera attached to the eyepiece of an ordinary optical microscope. Two photographs of each direction of a sample were obtained.

There are several points which need to be noted for an accurate measurement: boundary clearness in contact area of warp and weft yarns; hairiness of a



2.10 Measurement of weave angle.

Table 2.11 Measured weave angle

Sample	θ_1	θ_2	Sample	θ_1	θ_2
2	35.6	34.7	16	18.8	20
3	41.1	43.4	18	32.7	39.1
4	37.1	39.5	20	19.9	40.5
5	45.9	39.7	21	24.5	35.1
6	43	41.2	22	10.2	34.9
7	37.8	37.6	23	31.1	43
9	40.4	35	24	27.2	45.3
10	34.2	33.6	25	35.5	37.7
11	33.3	33.8	26	31.4	34.9
12	38.4	33.3	27	30.3	33.2
13	35.6	37.3	1	36.5	44.4
14	42.1	35.9	8	25.3	37.1

yarn; positioning the sample before measuring; irregularity of yarn structure; and calibration before testing.

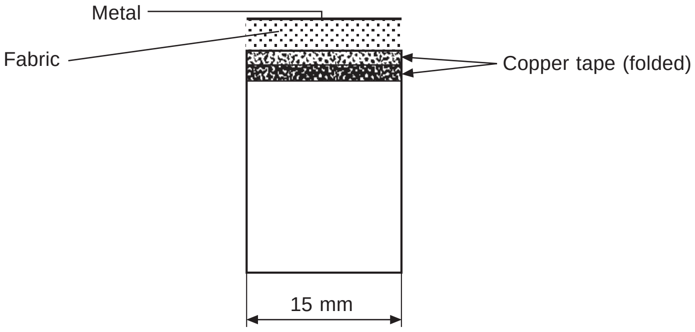
2.3.2 Scanning electron microscope

The scanning electron microscope (SEM), as its name suggests, is an electron optical instrument: it uses a beam of electrons to illuminate the specimen. The electron beam is generated with a gun, accelerated by a high voltage, and formed into a fine probe by a series of electromagnetic lenses. The electron-optical column through which the beam passes is held under a high vacuum to allow a free path for the electrons, and to prevent a high voltage discharge. The electron beam is rastered across the surface of the specimen by means of a series of deflection coils, and this raster is synchronous with that of a cathode ray tube (CRT). The signals produced, as a result of the beam being rastered across the specimen surface, are collected by an appropriate detector, amplified and displayed upon the CRT. The magnification of the image is the relationship between the length of the scan line on the specimen and the length of the scan line CRT.

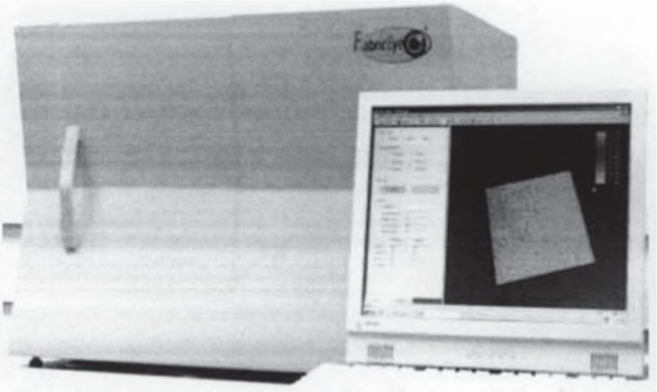
The electron beam striking a specimen surface requires a conducting path to earth in order to remove any electron charge that results. Conducting materials do not produce problems, but non-conducting materials may need a conducting coating applied to the surface to simplify operation. This second CRT is used specifically for photography. It has a much faster image decay rate than the viewing CRT, such that only a single scan line is visible at any one time. The screen itself is photographed, using Polaroid, 35 mm, 120 or 220 films; a conventional camera is used. Each line of the image is exposed to the emulsion, the camera shutter being held open for the duration of a single frame scan.

2.3.2.1 Experiment on fabric surface image

As shown in Fig. 2.11, a sample is stuck to a metal stub, the diameter of which is 15 mm, using adhesive double-sided tapes. The specimen must be coated with gold before testing. There are two reasons why we coat specimens prior to insertion into the SEM. First, because non-conducting specimens build up a surface charge through which secondary electron information is unable to penetrate, the image we view may be distorted both in signal level, and image form. Second, it is necessary in order to provide a surface layer that produces a higher secondary electron yield than the specimen material. To make the specimen easier to handle in the microscope (less charge and distortion), a sputter coating was used. In sputter coating a gold target is bombarded with heavy gas atoms. Metal atoms ejected from the target cross the discharge to deposit onto the surface of a specimen. A low vacuum environment is used (0.1–0.05 mbar), which, with the modern low voltage sputter coaters, enables metal to be deposited at up to 1 mm/s^{-1}. A photographic image of the fabric surface was taken with the magnification around 50.



2.11 Preparation of sample for SEM.



2.12 FabricEye®.

2.3.3 FabricEye®

2.3.3.1 Introduction

Pilling, wrinkle and hairiness on fabrics or garments are well-known phenomena, and these unpleasant appearance attributes can seriously compromise the fabric's acceptability. Currently, all pilling, wrinkle and hairiness testing systems available on the market are manual and subjective. These cannot provide an accurate, reliable and consistent assessment.

FabricEye® (shown in Fig. 2.12) was developed by the Institute of Textile and Clothing of the Hong Kong Polytechnic University led by Dr Jinlian Hu and Professor Edward Newton. It is an intelligent and comprehensive fabric surface inspection system which aims at tackling the inconsistency created by various subjective evaluations. The initial objective was pilling evaluation. Two patents applications have already been submitted for the mechanical design.

Quality grading standards, such as those described by AATCC and ASTM for pilling appearance evaluation, are subjective. There is always inconsistency among different experts due to different physical and psychological factors, such as fatigue and personal preference. Such evaluation is time- and money-consuming but unreliable. In today's business environment, quality is becoming more and more important; such subjective, old-fashioned, non-scientific evaluation is no longer effective and needs to be replaced.

FabricEye® is a system which was built with edge lighting capturing technology. It consists of a specially designed belt-driven machine together with intelligent software composed of several modules. Pilling, wrinkling, seam-puckering, hairiness and fuzziness were the analysis modules for objective evaluation.

2.13 Subjective evaluation of fabric appearance.

2.3.3.2 Traditional subjective assessments

Traditional assessments for fabric appearances like pilling, hairiness and wrinkle are basically subjective, with grading carried out by comparison between the fabric sample and the standard rating photographs as shown in Fig. 2.13. The process is thus rather reliant on the observers' experience. Assessment of fabric hairiness is even more arbitrary since there are no criteria which can be referred to. The process is thus rather subjective and the results generated are lacking in accuracy. The only way to improve the accuracy of the results is to have the specimen assessed by as many people as possible, and thus a fabric sample usually has to be inspected by at least three people, an evaluator, a supervisor and an approver, which means at least three times for one fabric. If a dispute arises, more people and laboratories will be involved. The process is rather time-consuming and the test results obtained are seemingly neither reliable/nor generally accepted.

Other quality standards for pilling or wrinkle evaluation, based on subjective evaluation like ASTM and AATCC, also suffer the many disadvantages listed below:

(1) **Inexperience:** people may lack the experience to appreciate and control the quality of the fabrics or garments. This will increase the incidence of rejection and the costs associated with it.
(2) **Lack of accuracy:** the evaluation will have bias and will not be accurate, due to the human factors involved.
(3) **Slow process:** humans may easily get weary after working for a long period of time and so the assessment process will be affected by human fatigue.
(4) **Inconsistency:** different people and environments will give rise to different opinions, preferences and results.
(5) **Other:** damaging and fading of the photographic standards will affect the result.

For visual assessment the data analysis confirmed that significant variations do exist within laboratories, and there are even larger variations between different laboratories. Thus, subjective evaluation does not give results which are consistent among different parties, at different places and at different times. All these factors can adjust perception and grading ability. In turn these can all affect the costs which arise from wrong decisions being made.

2.3.3.3 Overview of the FabricEye® system

Background

Since the 1950s, researchers attempted to investigate the characteristics of fabric appearance using computer and image technologies (Serra, 1982; Xu *et al.*, 1998; Tsai and Hsieh, 1999; Hu, 2001; Hu *et al.*, 2001, 2002a,b. They usually processed greyscale images, which were captured using change coupled device (CCD) camera. However, anisotropic light intensity with colour-patterned fabrics presented a problem with these pictures. Thus, other researchers began to develop new approaches to capture fabric images which are not affected by fabric patterns, such as the laser technique (Xu, 1998).

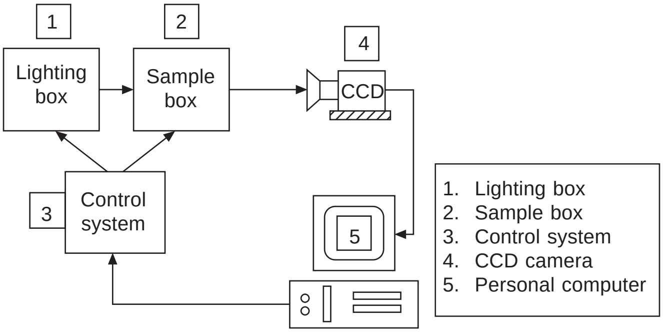
By using the laser technique, the three-dimensional profile of a fabric surface could be extracted; however, its limitations in the form of difficulty in practical operation and high instrumental cost combined with low precision hindered commercial development.

Because the above three techniques – manual, image technology and laser scanner – cannot fulfil the requirements of industry, Dr Hu Jinlian in the Institute of Textiles and Clothing of the Hong Kong Polytechnic University led her team to develop a digital system for the objective evaluation of fabric appearance. They were able to prove that the digital evaluation of fabric appearance is possible and feasible based on the following points:

- image processing techniques applied to many fields
- decrease in hardware costs
- improvement in quality and reliability of cameras
- powerful and effective tools for the evaluation
- user-friendly

Configuration of the FabricEye® system

FabricEye® includes five basic components as shown in Fig. 2.14: a lighting panel which supplies a constant amount of light; a closed black box where capture takes place avoiding the interruption from external lighting; a programmed electronic component to control the signals of several pieces of hardware; a high-speed industrial type CCD camera; and a standard personal computer equipped with analysis software.



2.14 System structure of FabricEye®.

FabricEye® system specification and requirements

The Fabric Eye® system specification and requirements are shown in Table 2.12.

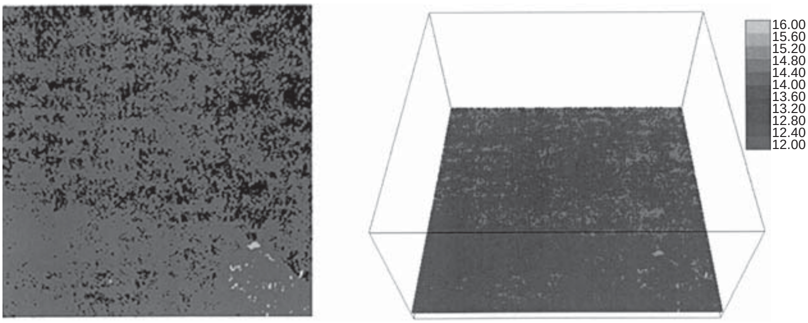
Information obtained from the FabricEye® system

In general, FabricEye® can provide a surface profile for the user. The surface profile can be displayed in two modes: a two-dimensional greyscale mode and a corresponding three-dimensional false-colour mode as shown in Fig. 2.15.

In the pilling evaluation modules, six features will be evaluated from the surface profile. They are the 'Average Measured Thickness', 'Average Pilling Counts', 'Pilling Size', 'Pilling Area', 'Pilling Height' and 'Pilling Circularity'.

Table 2.12 Fabric Eye® system specification and requirements

System specification	
CCD camera	Resolution: (640 × 480) pixels Shutter speed: 1/8000 seconds
Step motor	Phase number: 2
Dimension	[610 (L) × 310 (H) × 240 (W)] mm
Scanning and analysis time	~ 25 seconds and ~ 10 seconds
Computer requirements	
CPU	800 MHz
Memory	256 MB
Disk space	1 GB
Operating system	Microsoft Windows® 98/2000
Fabric sample requirements	
Dimension	[105 × 105] mm (Standard size for ASTM D3512)
Thickness	[0.2–10] mm
Type	Knitted and woven



2D Greyscale mode

3D False-colour mode

2.15 Displaying mode.

According to Xin *et al.*, (1999, 2002), these six parameters have very high correlation factors with the subjective grading and were thus the ones chosen to be summarised.

The principle of FabricEye®

The hardware of the instrument consists of lighting sources, sample mounting mechanism, sample running mechanism, high-speed CCD camera and scanner, image analysis software package, a commercial personal computer, and a specially designed control unit. Several patents and a trade mark have been registered.

In order to construct the three-dimensional profiles of fabrics, a CCD camera was used which has resolution of 640 × 480 pixels and took several periodically grabbed images to produce the image map.

To eliminate the effect of colour, a special lighting and sample holding system was developed, with new algorithms for the evaluation of fabric appearance attributes such as pilling, wrinkling, polar fleece fabrics, etc. Very good results have been achieved. Among them, one patent has been filed.

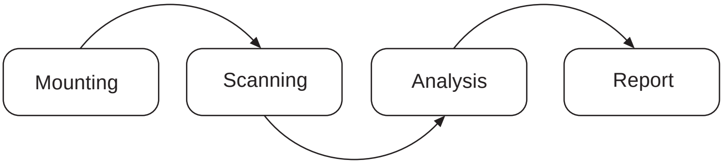
The software of the instrument consists of image capture, image display, image analysis and results output. The scanning time is below 25 sec and the analysis time is below 10 sec.

FabricEye® can produce a three-dimensional map of the fabric surface and extract prominent digital features to give a quantified description of fabric appearance. It can carry out grading as well as an experienced judge.

Evaluation procedure

FabricEye® was intentionally designed with the following features:

(1) automatic analysis with detailed report;
(2) ease of use so that minimum training would be required;
(3) measurement free of the effect from colours;

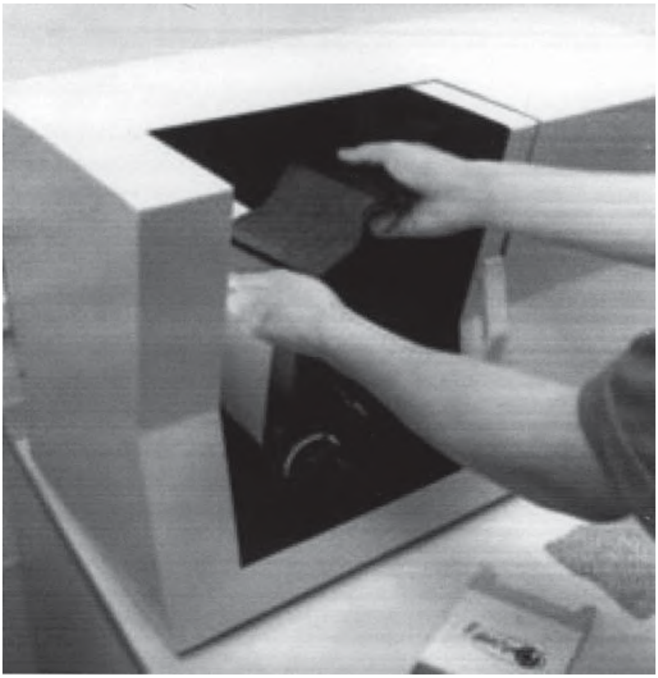


2.16 Evaluation procedure of FabricEye®.

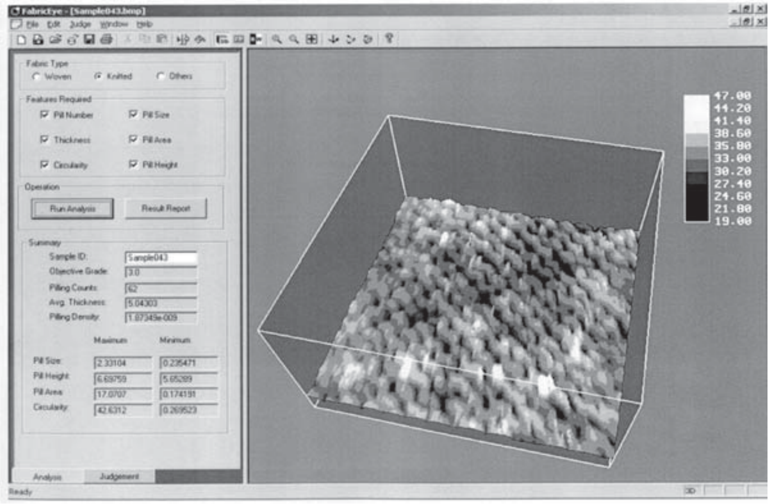
(4) reading generated quickly but repeatable;
(5) grading decision should be compatible with standards.

Considering the five issues above, fabric analysis by FabricEye® was reduced to only four steps, simply illustrated in the flow diagram given in Fig. 2.16, and outlined below.

Step 1 – mounting sample
Mount fabric sample on the testing belt (Fig. 2.17).



2.17 Mounting a fabric sample on the testing belt.



Fabric Type
○ Woven ● Knitted ○ Others

Features Required
☑ Pill Number ☑ Pill Size
☑ Thickness ☑ Pill Area
☑ Circularity ☑ Pill Height

Summary
Sample ID: Sample043
Objective Grade: 3.0
Pilling Counts: 62
Avg. Thickness: 5.04303
Pilling Density: 1.07349e-009

	Maximum	Minimum
Pill Size	2.33104	0.235471
Pill Height	6.69759	5.65289
Pill Area	17.0707	0.174191
Circularity	42.6312	0.269523

2.18 Generated fabric map.

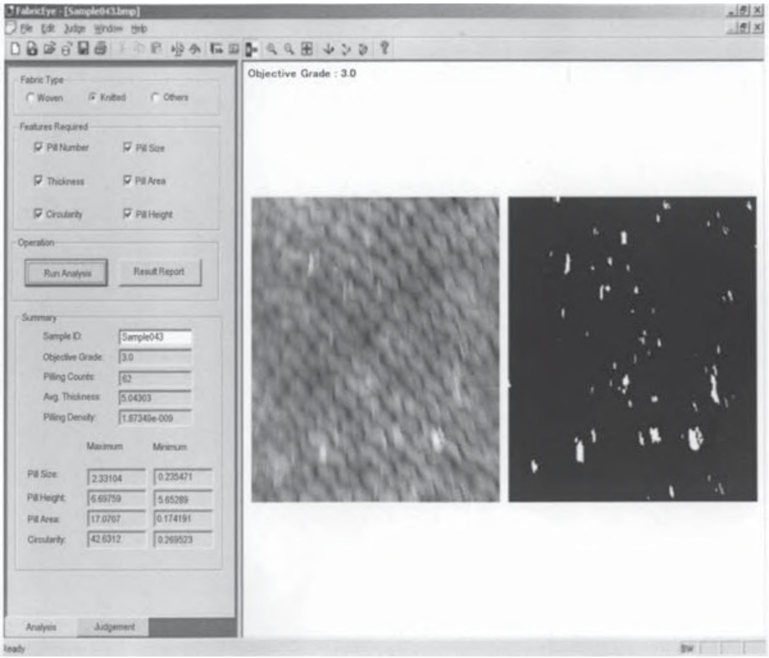
Step 2 – 3D surface map generation
Run the step motor to move the sample and simultaneously capture the images of fabric profile. Both processes are controlled by computer. Image software will automatically generate a three-dimensional surface map of fabric sample, shown in Fig. 2.18.

Step 3 – feature analysis
Automatic background balance, automatic threshold, automatic feature extraction and related image analysis techniques are applied in this step. Features of fabric surface, for example, pill number, pill size, pill height, and so on are extracted accurately. The quality grade of the sample is intelligently determined by these features. Feature analysis is illustrated in Fig. 2.19.

Step 4 – result report
In this step, the statistical result of these features is reported automatically; the user can easily open a special database to record these features or export them into a document. Figure 2.20 shows a results report.

The analysis of thickness in FabricEye®
One of the important features provided by FabricEye® is the analysis of surface roughness. The roughness measurement on fabrics characterises the fabric's surface from its nature and properties. This is actually an effective method to study the washing effect.

The analysis includes the following parameters: (1) average thickness, (2) relative smoothness, (3) surface skewness, and (4) relative flatness. These parameters will be illustrated in the following sections.



Objective Grade : 3.0

Fabric Type
○ Woven ● Knitted ○ Others

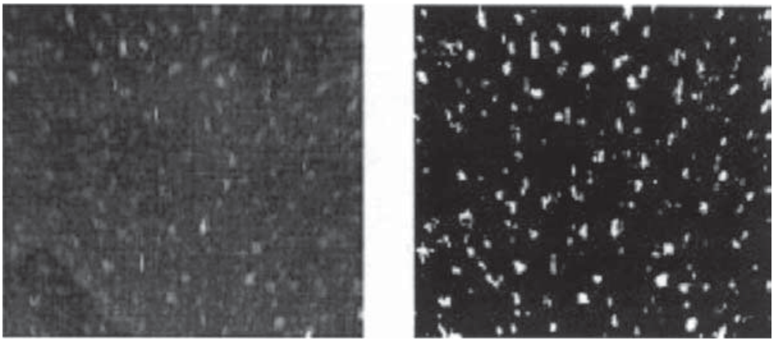
Features Required
☑ Pill Number ☑ Pill Size
☑ Thickness ☑ Pill Area
☑ Circularity ☑ Pill Height

Summary
Sample ID: Sample043
Objective Grade: 3.0
Pilling Counts: 62
Avg. Thickness: 5.04303
Pilling Density: 1.87349e-009

	Maximum	Minimum
Pill Size:	2.33104	0.235471
Pill Height:	6.69759	5.65289
Pill Area:	17.0707	0.174191
Circularity:	42.6312	0.269523

2.19 Feature analysis.

Fabric pilling evaluation report
Sample ID: sample 001
Objective grade: 1.0



Statistics
(All dimensions in mm)
Average pilling count: 4.2813
Average thickness: 3.85
Pilling density: 1.33e–008

	Maximum	**Minimum**	**Average**
Pill size:	1.49	0.16	0.52
Pill height:	4.76	3.97	4.23
Pill area:	7.01	0.08	1.23
Pill circ.:	53.53	0.02	8.69

2.20 Result report.

Average thickness

The traditional method using a clamping device is a kind of compressive measurement taken over a relatively large area. FabricEye® takes more than 2 million uncompressed measurements over the entire sample surface:

$$\text{thickness} = \Sigma \frac{n}{N}, \qquad [2.3]$$

where n is the value of sampling points and N the total number of sampling points over the surface.

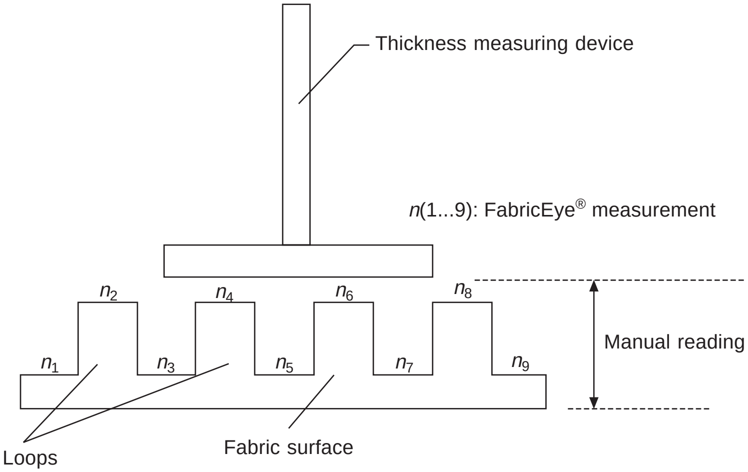
The difference between measurements obtained manually and those obtained using FabricEye® can be used to describe the hairiness and fuzziness of fabrics.

Suppose that TF is the average thickness measurement by FabricEye® and TM is the average thickness measurement by manual device. There are three possible situations:

- **Situation 1 (*TF* > *TM*):** The measurement by FabricEye® is greater than by manual. This is the most frequently observed situation. For most of the common fabrics, hairiness and fuzziness exist. Since the reading from FabricEye® is non-compressive, the hairiness and fuzziness contributed to the height. The clamping device pressed down the hairs and thus the reading taken from it is lower than from FabricEye®.

  In other words, in studying the washing effect, the value of the difference is meaningful. The more the difference, the more hairy and fuzzy the fabric is. The washing effect is relatively effective.
- **Situation 2 (*TF* = *TM*):** The measurements from FabricEye® and manual are equal or almost the same. This indicates that the fabric is quite flat. It could be either a woven fabric or an unwashed fabric in which the celluloses have not yet been digested. It implies that the washing method is ineffective and should be revised.
- **Situation 3 (*TF* < *TM*):** The situation in which the FabricEye® reading is smaller than the manual measurement rarely occurs. It has nothing to do with the washing, but is probably due to the physical structure and components of the fabric. It is usually a knitted fabric with large loop. The yarn loop density is comparatively low. Figure 2.21 could explain the phenomenon.

  The contact area of the clamp of the thickness measuring device is usually relatively large and the force from the device is not sufficient to press the loop structure but only the hairiness and fuzziness. The relatively harder loop structure blocks the in-depth measurement. However, FabricEye® takes numerous sample readings over the entire surface. The thickness is an averaged height value from the sampling points. Therefore, the measurement from FabricEye® would be lower than the manual one in this case.



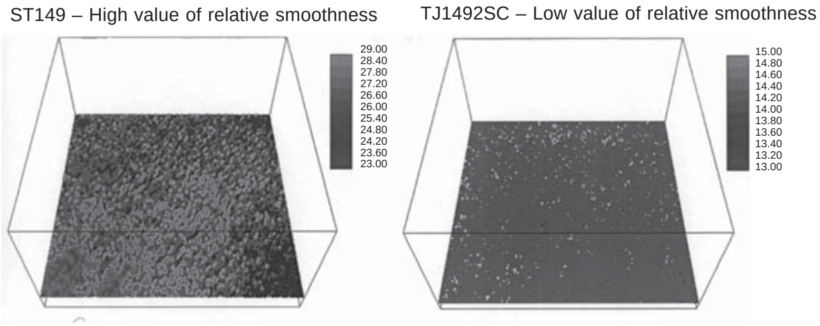
2.21 Difference of measurement between manual and FabricEye®.

Relative smoothness

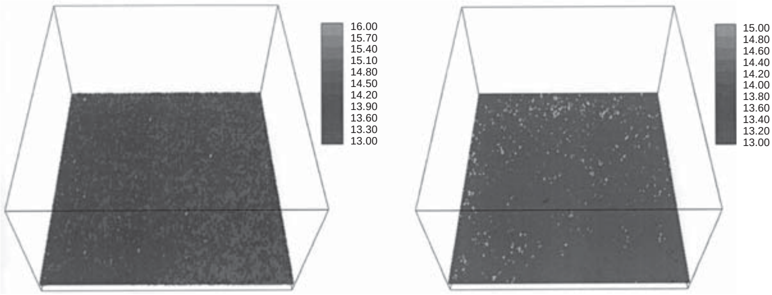
The relative smoothness is a global analysis of the surface roughness, as shown in Fig. 2.22. It provides an overall idea of how much variation there is on the surface. More rough or strongly patterned fabrics will give a greater value. The value is useful in comparative studies between fabrics. Equation 2.4 governs the relative smoothness:

$$\text{relative smoothness} = 1 - \frac{1}{1 + \sigma^2} \qquad [2.4]$$

where σ^2 is the variance of the height of sampling points.



2.22 Relative smoothness demos. Left: sample showing high degree of relative smoothness. Right: sample showing low degree of relative smoothness.



2.23 Surface skewness demos. Left: (negative value) few raised peaks appear in light grey. Right: (positive value) few sunken zones appear in dark grey.

Surface skewness

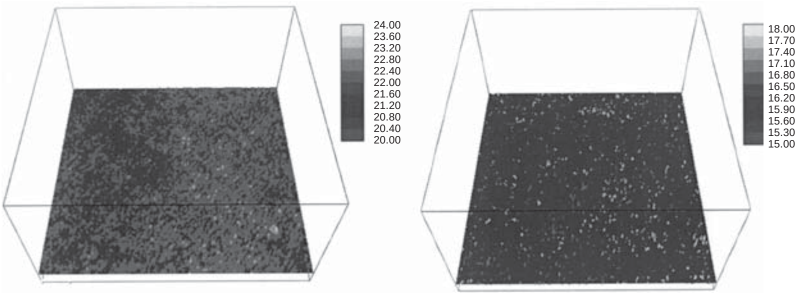
Surface skewness is a study of the third degree of the height response as shown in Fig. 2.23. Its value indicates if any extrema exist on the surface. A positive value indicates the presence of some sunken zone, while a negative value indicates a raised zone. Equation 2.5 governs surface skewness:

$$\text{skewness} = \frac{E(n - \bar{n})}{\sigma^3}, \qquad [2.5]$$

where E is the expected value, $\bar{n}$ is the average value of sampling points and σ is the standard deviation of the height of sampling points.

Relative flatness

Relative flatness is a localised study of the amount of extrema as shown in Fig. 2.24. It is actually a fourth degree of the height response. Its value indicates if the amount of extrema present is serious. The greater the value, the more corresponding extrema would be observed. Equation 2.6 governs relative flatness:



2.24 Relative flatness demos. Left: (lower value) fewer extrema (in white) could be observed. Right: (higher value) more extrema (in white) could be observed.

$$\text{relative flatness} = \frac{E(n - \bar{n})}{\sigma^4}, \qquad [2.6]$$

where E is the expected value and σ is the standard deviation of the height of sampling points.

Applications

FabricEye® further summarised the evaluation process by giving the specimens an objective grade. The rapid results from the equipment allow the fabric buyers to make decisions quickly. Furthermore, quality evaluation laboratories can release manpower to carry out other experiments with a higher requirement for technical input. Manufacturers can further utilise the other data obtained for product development and characterisation.

With future integrated modules, FabricEye® can be applied to the fashion and textile industry, laundry services, and custom inspection for the different appearance evaluation of pilling, wrinkling, surface hairiness, texture/density, seam puckering and polar fleece fabrics and garments.

To summarise, FabricEye® brings many benefits to the industry in terms of better quality management, with quick response and lower production costs, as well as quality production, with efficient quality control and informative and objective statistics. It can also eliminate arguments due to different subjective judgments from different inspectors.

2.4 Complex deformation measurement

2.4.1 Introduction

The drape of a fabric in a broader sense refers to the manner in which the fabric hangs, shapes and flows on the model form, such as on the body and furniture, by gravity when only part of it is directly supported. In some literature, wrinkling, buckling, handle and bending may mean drape. In the present context, the dominant role played by the gravity of the fabric in drape is emphasised. The folding from fabric drape which takes up a complex three-dimensional form with double curvature is unique for drape, but single curvature of fabric deformation, such as the cantilever test, is also included in the present review, as long as fabric deformation results from its own weight.

Research into this theoretically complicated and practically important topic originated with Peirce in 1930. For several decades, this paper has been regarded as a benchmark and a source of investigation for many researchers. Particularly since the year 2000, the investigation of fabric drape has attracted the attention of many researchers, partly because of the attempt to realise the clothing CAD system by introducing fabric properties in which the fabric drape is the key element. The intention here is to make a comprehensive survey of the existing research into fabric drape and its application to the textiles and clothing industries since Peirce. The contents consist of: experimental study and evaluation methods; empirical study of the relationship between fabric drape and mechanical properties; assembling methods, theoretical investigation, analytical and numerical prediction; current status and future trends of research in this area are also included. It consists of two parts. The first part of this review deals with test and evaluation of drape, and empirical study carried out by textile specialists. The second part will discuss theoretical aspects and numerical simulation as well as its applications.

2.4.2 Cantilever methods

In the past, the cantilever test was mainly used to determine fabric stiffness, e.g. bending rigidity (constant and whole bending curve) and/or possibly frictional couple. Its association with fabric drape and extensive discussion here are due to the following reasons: first, the cantilever test utilises the response of a fabric under its own weight, which is essentially the drape behaviour of a fabric, but in only two dimensions; second, bending properties obtained for this test are the key element for predicting fabric drape generally; third, many numerical or theoretical investigations into fabric drape used the standard fabric cantilever test to verify their mechanics models and/or the accuracy of their software programmes. Finally, some investigations for fabric handling related to fabric drape are based on Peirce's cantilever theory (Postle and Postle, 1992).

Cantilever methods for the evaluation of fabric drape were first introduced to textile specialists by Peirce (1930), based on the recognition that stiffness has a large effect on drapeability. In his original paper, nine types of cantilever were proposed for different types of fabrics.

The standard tester, called a flexometer, which has now become the standard Shirley Stiffness Tester, was described in detail by Peirce (1930). On this tester, the angle through which a specimen of cloth droops when a definite length is held out over an edge can be measured. The specimen is a rectangle with a large length to width ratio (6:1). By means of a mathematical formula, this angle is converted into a term called 'bending length', which is a measure of fabric drapeability in two dimensions; Peirce even called it 'drape stiffness'.

Peirce mentioned in the same paper another eight types of fabric cantilevers to compensate for the shortness of the rectangle cantilever. Various modifications of the method had been worked out to deal with those fabrics which were unsuitable for the standard method. For example, for very stiff such as starched and ironed fabric, a weight can be added to the free-end of the specimen, called a weighted rectangle. For a very flimsy fabric, a triangle cantilever may be used. A material too stiff, but curling badly when tested as a weighted rectangle, may be better dealt with as a triangle weighted at the tip. Because the curling is not so pronounced in a broader strip, Peirce also suggested another cantilever with a wider (6 in) strip. With the broader instrument, it is also possible to test a specimen cut in circular form. For fabrics where the tendency to curl is so pronounced that the strip takes a complete twist, a long specimen of 20 cm is cut, with the middle marking a dot, and the two ends placed together to form a pear- or ring-shaped loop. The depression of the middle point is much the same as for a strip of the same length.

F.R.L. Testing Machines Inc. (1980) reported that the F.R.L. Cantilever Bending Tester is capable of testing thin sheet material, textiles and other flexible materials, including carpets. After Peirce and F.R.L. Cantilever, several versions of the tester were designed. Some improvements in this test were made, particularly in terms of automation.

Kalyanaraman and Siveramakrishnan (1984) designed an electronic cantilever meter based on optoelectronic principles. Their instrument has the same accuracy as the Shirley Stiffness Meter and works on the same principle, but the measurement is objective and could easily be automated.

The FAST system developed by CSIRO in 1993 consists of a cantilever bending meter. The principle for FAST-2 is very similar to that of the Shirley Stiffness Tester in which the fabric bends under its own weight until its leading edge intercepts a plane at an angle of 41.5° from the horizontal. Compared with the Shirley Stiffness tester, the FAST-2 was designed to test a wider specimen (50 mm), even though any sample width from the standard 2.45 cm up to 50 mm can be employed. In addition, this instrument encloses totally the electronics and detection apparatus. The fabric leading edge is detected, as it is moved across to the measurement cavity, initiating the length measurement, then as it cuts a light beam inclined at 41.5° to the horizontal. After a settling and adjustment period the bending length is displayed digitally.

Russell (1994) reported an alternative instrument for the measurement of fabric bending length in contrast with the commercial Shirley Stiffness Tester and the FAST-2 bending meter. He pointed out that both instruments use a sliding bar and encounter problems with some fabrics, such as pile fabrics or those made of filament yarns. For these slippery or easily deformed fabrics, with this simultaneous weighting and sliding procedure, the slider can slip over the surface of filament fabrics and cause the fabric to cockle as it is slid along the platform, leading to wrong bending lengths. In addition, they cannot be used at all on slivers, rovings or yarns. For this purpose, he developed a testing instrument that combines the principles of the Shirley and FAST-2 testers with elements of a comb sorter apparatus used for fibre distribution.

Clapp *et al.*, developed an indirect method of measuring the moment–curvature relationship for fabrics (Clapp *et al.*, 1990; Clapp and Peng, 1991). At the same time, they developed a method to measure the draped profile of the cantilever. Deformed co-ordinates were recorded as a fabric sample was cantilevered under its own weight from a fixed support. The advantage of this method is that fabric non-linear bending behaviour, inherent in most fabrics, is readily obtained, unlike in the traditional cantilever beam test. Moreover, the draped image obtained by using a laser sensor can be used for the verification of the numerical simulation results.

Potluri *et al.* (1996) also developed an experimental technique to verify their numerical method for the capability to compute for general situations. A laser triangulation sensor, attached to a robot arm, was used for measuring the cantilever profile of the fabric samples. A manipulating device positions the fabric sample as a cantilever of specified length. The laser scans along the centre line of the fabric cantilever. The x co-ordinates are obtained from the robot position and the y co-ordinates are obtained from the output signal of the triangulation sensor.

2.4.3 Drapemeter

Cusick (1961) and Chu *et al*. (1950) made a great contribution to the practical measurement of fabric drape. The current standard so-called drapemeter is the result of their effort, in which the drape coefficient, the ratio of projected area to specimen's original area, is determined. The drape coefficient can provide an objective description of the deformation, although it is not a complete description. A low drape coefficient indicates easy deformation of a fabric. The advantage of this method over the cantilever is its capability to test the three-dimensional drape feature, and it can thus differentiate between the paper and a textile fabric. Further investigations or changes on this type of drapemeter are limited, but advances in this method can also be traced.

Vangheluwe and Kiekens (1993) measured the drape coefficient using image analysis. A CCD camera is mounted centrally above the drapemeter. This camera sends the image to a monitor and a frame grabber in a personal computer. The frame grabber digitises the image. The drape coefficient is calculated using a ratio not of masses but of areas. Calibration is carried out by recording the image of the drape tester without a test sample. The image analysis system presents a number of advantages, which makes it preferable to the traditional measuring method. A test using the suggested method will take no more than 10 sec, whereas the cut-and-weigh method easily requires more than 5 min. Moreover, the results obtained when using the cut-and-weigh method are subjective because the drawing and cutting are influenced by the laboratory assistant. By using this system, the authors investigated the time dependence of drape coefficient at 10 min intervals.

Collier *et al*. designed a digital drapemeter to measure fabric drape coefficient by using photovoltaic cells (Collier and Collier, 1990; Collier, 1991; Collier *et al.*, 1991a, b). This drapemeter utilises the principle of the standard experimental drapemeter and applies a bottom surface of photovoltaic cells to determine the amount of light blocked by a fabric specimen draped on a pedestal. A digital display gives the amount of light being absorbed by the photovoltaic cells, which is related to the amount of drape of the fabric specimen. This principle was quickly adapted by textile researchers in China.

Stylios *et al*. (1996) developed a new drapemeter, which measures the drape of any fabric both statically and dynamically, in true three-dimensions, by using a CCD camera as a vision sensor. This system, called the Marilyn Monroe Meter (M3), has been used to measure real fabric drape behaviour, and is being used to verify their theoretical prediction model. The draped profile of the specimen can be taken and presented on a computer.

2.5 References

AATCC, *Technical Manual of the American Association of Textile Chemists and Colorists*, http://www.aatcc.org.

ASTM-D3511 (2002), Standard test method for pilling resistance and other related surface changes of textile fabrics: brush pilling tester, New York, ANS I.

ASTM-D3512 (2002), Standard test method for pilling resistance and other related surface changes of textile fabrics: random tumble pilling tester, New York, ANS I.

ASTM-D3514 (2002), Standard test method for pilling resistance and other related surface changes of textile fabrics: elastomeric pad, New York, ANS I.

ASTM-D4970 (2002), Standard test method for pilling resistance and other related surface changes of textiles fabrics: martindale tester, New York, ANS I.

BS3356 (1990), Method for determination of bending length and flexural rigidity of fabrics.

BS2862: (1984), ISO 7211/2 Methods for determination of number of threads per unit length (withdrawn, superseded)

Chu C C, Cummings C L and Teixeira N A (1950), Mechanics of elastic performance of textile materials, part V: A study of the factors affecting the drape of fabrics – the development of a drape meter, *Text Res J*, **20**, 539–548.

Clapp T G and Peng H (1991), A comparison of linear and nonlinear bending methods for predicting fabric deformation in automated handling, *J Text Inst*, **82**, 341.

Clapp T G, Peng H, Ghosh T K and Eischen J W (1990), Indirect measurement of the moment-curvature relationship for fabrics, *Text Res J*, **60**(9), 525–533.

Collier B J (1991, Fall), Measurement of fabric drape and its relation to fabric mechanical properties and subjective evaluation, *Clothing and Textiles Research Journal*, **10**, 46–52.

Collier B J and Collier J R (1990), CAD/CAM in the textile and apparel industry, *Clothing and Textiles Journal*, **8**(3), 7–13.

Collier J R, Collier B J, Gina O’tool and Sargand S M (1991a), Drape prediction by means of finite element analysis *J Text Inst*, **82**, 96–107.

Collier J R, Collier B J, Gina O’tool and Sargand S M (1991b), Development of a digital drape tester, *ACPTC combined proceedings*, 35.

Cusick G E (1961), *The Measurement of Fabric Drape*, (PhD thesis, University of Manchester Institute of Science and Technology).

F R L Cantilever bending tester (1980 Aug), New York 11701, Testing machines Inc 400 Bayview Ave, Amityville, 1 p News release literature.

Grosberg P (1966), The mechanical properties of woven fabrics part II: the bending of woven fabrics, *Text Res J*, **36**, 205–210.

Grosberg P and Park B J (1966), The mechanical properties of woven fabrics part V: the initial modulus and the frictional restraint in shearing of plain weave fabrics, *Text Res J*, **36**, 420–431.

Grosberg P and Swani N M (1966), The mechanical properties of woven fabrics part IV: determination of the bending rigidity and frictional restraint in woven fabrics, *Text Res J*, **36**, 338–45.

Hu J L (2001), Digital system for the objective evaluation of fabric appearance, *Proc 6th Asian Textile Conference – Innovation & Globalization* Aug. 22–24, Hong Kong Polytechnic University, Hong Kong.

Hu J L, Xin B J and Yan H J (2001), Subjective and objective evaluation of polar fleece fabric appearance after abrasion, *Proc Technitex 2001 – the 1st Autex Conference*, June 26–29, Povoa de Varzim, Portugal.

Hu J, Xin B and Yan H (2002a), Measurement and modeling of 3D wrinkes in fabrics, *Text Res J*, **72**, 863–870.

Hu J, Xin B and Yan H (2002b), Classifying fleece fabric appearance by extended morphological fractal analysis, *Textile Res J*, **72**, 879–885.

Kalyanaraman A R and Siveramakrishnan A (1984), Electronic fabrics stiffness meter – performance evaluation with the known instruments, *Text Res J*, **54**(7), 479–484.

Kawabata S (1982), The development of the objective measurement of fabric handle, *Proc First Japan-Australia joint symposium on objective specification of fabric quality, mechanical properties and performance*, Kyoto, Textile Machinery Society, Japan, 31–59.

Lindberg J, Waesterberg and Svenson R (1960), Wool fabrics as garment construction materials, *J Text Inst*, **51**, T1475–1493.

Ly N G, Tester D H, Buckenham P, Roczniok A F, Brothers M and de Jong S (1988), *ITO Report No 11*, Paris Meeting.

Ly N G, Tester D H. Buckenham P, Roczniok A F, Adriaansen A L, Scaysbrook F and De Jong S (1991), Simple instruments for quality control by finishers and tailors, *Text Res J*, **61**(7), P402–406.

Manual for KES-FB, 1–4

Manual For VID system, UMIST

Peirce F T (1930), The handle of cloth as a measurable quality, *J Text Inst*, **21**, 337–416.

Peirce F T (1937), The geometry of cloth structure, *J Text Inst*, **28**, P45–96.

Postle J R and Postle R (1992), Fabric bending and drape based on objective measurement, *Clothing Sci & Tech*, **4**(5), 7–15.

Potluri P, Atkinson J and Porat I (1996), Departments of textiles and mechanical engineering, large deformation modelling of flexible materials, *J Text Inst*, **87**(1), 129–151.

Russell S J (1994), Alternative instrument for the measurement of fabric bending length (Univ of Leeds); (Letter to Editor), *J Text Inst*, **85**(1), 82–83.

Serra J (1982), *Image Analysis and Mathematical Morphology*, *Vol I*, New York, Academic Press.

Stylios G K, Wan T R and Powell N J (1996), Modelling the Dynamic Drape of Fabrics on Synthetic Humans in a Virtual Fashion Show, *Int J Clothing Sci & Tech*, **8**(3), 95–122.

Tsai D M and Hsieh C Y (1999), Automated surface inspection for directional textures, *Image and Vision Computing*, **18**, 49–62.

Vangheluwe L and Kiekens (1993), Time dependence of the drape coefficient of fabrics, *Int J Clothing Sci & Tech*, **5**, 5–8.

Xin B J and Yu X F (1999), Automatic measurement of the yarn density of woven fabric, *J China Text Univ*, **25**, 34–37.

Xin B, Hu J and Yan H (2002), Objective evaluation of fabric pilling using image analysis techniques, *Textile Res J*, **72**, 1057–1064.

Xu B, Cuminao D F and Keyes N M (1998), Evaluating fabric smoothness appearance with a laser profilometer, *Text Res J*, **68**, 900–906.