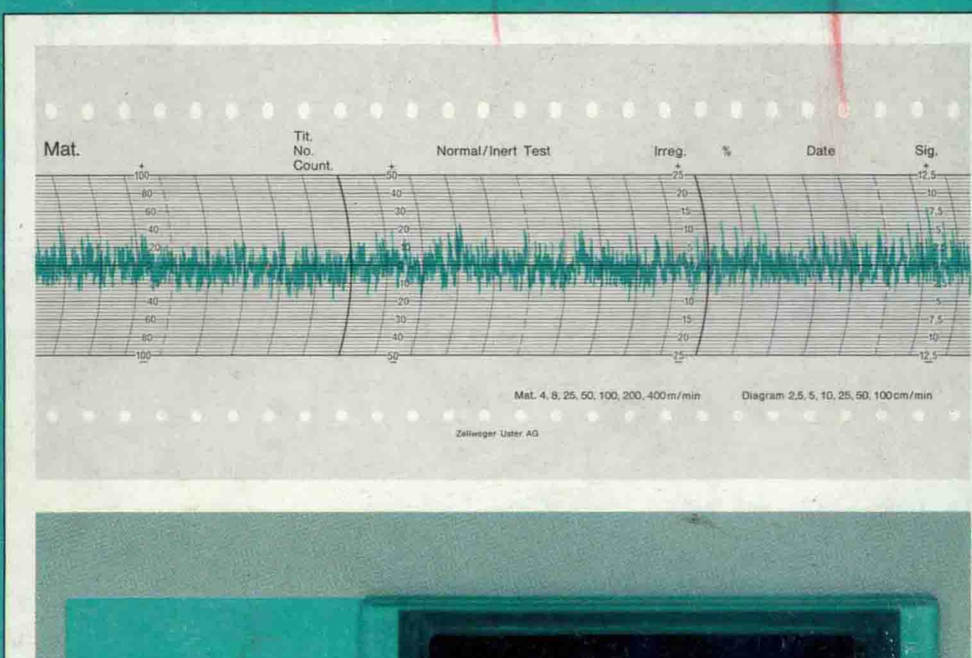
The Textile Institute

Textile Progress
Volume 14
Number 3/4

Yarn Evenness

K Slater



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Yarn Evenness

A critical appreciation of recent developments by
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ISSN 0040-5167
ISBN 0 900739 85 1

Use has been made of *World Textile Abstracts*, published by the Shirley Institute, in tracing many of the references cited in this review.

Textile Progress will be available on microfilm twelve months after publication from University Microfilms Limited, St John's Road, Tylers Green, High Wycombe, Bucks, HP10 8HR.

Printed by Stott Brothers Limited, Halifax, England

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TEXTILE PROGRESS

YARN EVENNESS

By K. Slater, M.Sc., Ph.D., C.Text., F.T.I.

1. INTRODUCTION: THE MEANING AND IMPORTANCE OF YARN EVENNESS

1.1 Evenness and Irregularity

Non-uniformity in a variety of properties exists in many textile products. There may be a disparity in colour or shade between different parts of the same article. The thickness of a sheet, such as a felt or a film, can vary from place to place. The components of a blend can change in proportion from one region of a fibre assembly to another. Strength, abrasion-resistance, water absorption, concentration of finishing agent, surface appearance, and many other fabric properties can differ with test-specimen position in the sample. In yarns, there can be a variation in twist, bulk, strength, thickness, or fineness along the length. It is this last property, the variation in fineness, that is usually understood to be meant by the term 'yarn evenness'.

The property, commonly measured as the variation in mass per unit length along the yarn, is a basic and important one, since it can influence so many other properties of the yarn and of fabric made from it. Such variations are inevitable, because they arise from the fundamental nature of textile fibres and from their resulting arrangement. A yarn in which the variations in mass per unit length are small is said to be even, while one in which this quantity exhibits considerable changes is regarded as irregular. It is the attempt to quantify the differences between yarns in this respect that has interested textile scientists for many decades and is the basis of all work on yarn evenness or yarn irregularity.

1.2 Fibre Characteristics

A textile fibre is a peculiar object. It has no truly fixed length, width, or thickness, nor are its shape and cross-section constant. Growth (of natural fibres) or production factors (for the man-made fibres) are responsible for this situation. An individual fibre, if examined carefully, will be seen to vary in cross-sectional area along its length. This may be the result of variations in growth rate, caused by dietary, metabolic, nutrient-supply, seasonal, weather, or other factors influencing the rate of cell development in natural fibres. For man-made fibres, production parameters such as polymer-viscosity changes, roughness of the spinneret orifice, variations in extrusion pressure or rate, filament-drawing-speed changes, and other such factors are responsible for the non-uniformity of cross-section. The length of a fibre, too, is not fixed. Because fibre-forming polymers are elastic, the linear dimension will be dependent on the tension applied to the two ends of the fibre. In addition, the ends themselves are often indeterminate as a result of non-uniform breaking or of natural-growth factors.

Surface characteristics also play some part in increasing the variability of fibre shape. The scales of wool, the twisted arrangement of cotton, the nodes appearing at intervals along the cellulosic natural fibres, and the frequent discontinuities along the silk filament are all examples of this phenomenon. In synthetic fibres, the presence of a delustrant or other additive can similarly modify the cylindrical shape that is usually assumed to exist and thus introduce a variability into the surface geometry.

1.3 Fibre Arrangement

The individual idiosyncrasies of each fibre are compounded when fibres are examined in the mass, not only by additive behaviour but also by the way in which fibres tend to become arranged when they are combined together in some form of structure. This fact arises again from the peculiar nature of textile units.

If one end of a fibre, placed on a smooth surface, is pushed, the other end does not necessarily move away, because the fibre is not rigid. In this respect, a textile fibre differs from virtually every other solid object; a consideration of the behaviour of metals, wood, glass, or similar substances will confirm this point. Hence, manipulation of a fibre, during its processing into fabric form, is an immensely complex combination of mechanical movements, usually requiring some degree of compromise. The desirable results of relocating large numbers of fibres at high speeds and of arranging them in some well-ordered manner tend to be incompatible, so that some balance between them normally has to be struck. If the fibres happen to be assembled into the form of the twisted strand that constitutes a yarn, it is small wonder that unevenness can occur along this strand.

There are, however, additional arrangement factors, which complicate the situation still further. The fibres that form the yarn are not arranged in any very orderly manner. Although the general trend is one of orientation along the yarn axis, each individual unit can, and does, deviate appreciably from this average behaviour. Fibres are not laid precisely end-to-end, so that overlaps and gaps are omnipresent throughout the structure. As a result of yarn twist, any one fibre will be arranged in an approximately spiral manner around the axis, but even this deviation from linearity is not orderly. Superimposed upon the spiral form is a series of folds, kinks, doublings, and similar types of disarrangement of the fibre.

In addition, other factors that arise at some stage during the production of a yarn can increase the disorder. Knots, neps, slubs, and other yarn faults can be introduced, accidentally or deliberately, during the process. When a yarn breaks, a knot may be used to join the broken ends. Tangled fibres, arising during any part of the manipulative procedure, may not be separated completely at the appropriate stage and may pass on to form a nep which remains in the yarn. Minor faults in the drafting operation can cause 'bunching' of fibres, leading to a slub, or thick place, in the yarn. The mechanical forces exerted on fibres may give rise to some disarray, so that the bulk (i.e., the ratio of fibre to air in the yarn cross-section), or the tension in individual fibres, can vary from place to place along the yarn. The resulting lack of homogeneity will add to the lack of uniformity of mass distribution within the yarn.

1.4 The Effects of Fibre Behaviour

These peculiarities in the shape and arrangement of fibres are directly responsible for the phenomenon known as yarn irregularity. It is obvious that, if a yarn is hypothetically sliced into microscopically thin sections along its length, these sections will not be identical. The arrangement of fibre sections and air space will vary from one yarn section to another. The size of individual fibre sections will vary. The number of fibre sections will change in successive segments. The cross-sectional area of each section will be different from that of all others. The mass of each section will also differ from that of others.

If, instead of microscopically thin sections, we choose a reasonable, fixed, short length of yarn as our basis of measurement, it is entirely feasible to measure the average cross-sectional area, the number of fibres present, or the mass for each unit of length and, in this way, to obtain quantitative data for deriving an expression for the evenness of the strand. If the yarn properties are then examined in conjunction with such data, it is logical to expect that a thin region of the yarn, with fewer fibres, a smaller cross-section, or a lower mass, will have less strength than a thicker region, where more fibres and a greater mass and stress-bearing area are present. Perhaps less obvious is the fact that, in thin regions, yarn twist tends to be higher; since the resistance to deformation is lower in such regions, increased distortion of the structure can be tolerated there. Thus, in a more uniform yarn, strength will tend to be higher and twist to be less variable than in an uneven yarn, a fact that can have immense significance in the quality of textile products.

1.5 The Importance of Yarn Evenness

As can now be realised, irregularity can adversely affect many of the properties of textile materials. The most obvious consequence of yarn evenness is the variation of strength along the yarn. If the average mass per unit length of two yarns is equal, but one yarn is less regular than the other, it is clear that the more even yarn will be the stronger of the two. The uneven one must contain thinner (and hence weaker) regions than the even one as a result of irregularity, since the average linear density is the same. Thus, an irregular yarn will tend to break more easily during spinning, winding, weaving, knitting, or any other process where stress is applied. In addition, the increased variability in thickness will tend to increase the likelihood of snagging, so that yarn-breakage problems at a point where any constriction is present will be compounded. This will be most apparent at, for example, the eye in a heald or knitting needle, or at the traveller in ring-spinning. Apart from the reduction in processing speeds necessitated by the requirement to mend such breaks, their presence will adversely affect the appearance, durability, and hence quality of the cloth produced from the yarn. Thus, an uneven yarn can directly affect the costs of production, the profit obtained, and the likelihood of rejection of a product.

A second quality-related effect of uneven yarn is the presence of visible faults on the surface of fabrics. If a large amount of irregularity is present in the yarn, the variation in fineness can easily be detected in the finished cloth. The problem is particularly serious when a fault (i.e., a thick or thin place) appears at precisely regular intervals along the length of the yarn. In such cases, fabric-construction geometry ensures that the faults will be located in a pattern that is very clearly apparent to the eye, and defects such as streaks, stripes, barré, or other visual groupings develop in the cloth. Such defects are usually compounded when the fabric is dyed or finished, as a result of the twist variation accompanying them.

As already mentioned, twist tends to be higher at thin places in a yarn. Thus, at such locations, the penetration of a dye or finish is likely to be lower than at the thick regions of lower twist. In consequence, the thicker yarn regions will tend to be deeper in shade than the thinner ones and, if a visual fault appears in a pattern on the fabric, the pattern will tend to be emphasized by the presence of colour or by some variation in a visible property, such as crease-resistance, controlled by a finish.

Other fabric properties, such as abrasion- or pill-resistance, soil retention, drape, absorbency, reflectance, or lustre, may also be directly influenced by yarn evenness. Thus, the effects of irregularity are widespread throughout all areas of the production and use of textiles, and the topic is an important one in many areas of the industry.

1.6 The Scope of This Issue

In this issue of *Textile Progress*, published work on the subject of yarn evenness is to be reviewed. The issue is arranged in five sections, dealing, respectively, with the theory, causes, measurement, effects, and reduction of irregularity. In general, only the more recent work (i.e., within the past ten years) is to be included, though it is sometimes necessary to venture further back into the past, particularly when theoretical work is being reviewed, for the sake of completeness and to ensure that as little important material as possible is excluded. In this way, it is hoped that the book will serve as a more complete text on the subject of yarn evenness than would be the case if it were to be restricted merely to a critical appraisal of modern work only.

2. METHODS OF DESCRIBING EVENNESS

2.1 Single-value Methods

2.1.1 Coefficient of Variation

In handling large quantities of data statistically, the coefficient of variation (CV) is commonly used to define variability and is thus well-suited to the problem of expressing yarn evenness. Many authors[1–12] have used it as the basis for developing new ideas or for comparative studies, and it is currently probably the most widely accepted way of quantifying irregularity. It is given by the expression:

$$CV = \frac{s}{\bar{x}},$$

where s is the standard deviation and $\bar{x}$ the mean of a number of measured estimates of the mass per unit length of the yarn.

The property is usually expressed as a percentage, calculated as:

$$CV\% = 100 \cdot \frac{s}{\bar{x}} .$$

Its precise mathematical definition is:

$$CV\% = \frac{100}{\bar{x}} \cdot \sqrt{\frac{1}{t} \int_0^t (x_n - \bar{x})^2 \cdot dt} .$$

2.1.2 Irregularity, U%

The parameter U appears to be used almost exclusively by the manufacturers of the well-known Uster test equipment and is discussed in one of their publications[13]. It may be defined in terms of the expression:

$$U = \frac{a}{\bar{x}t} ,$$

where a is the total area, in time t, between a curve expressing instantaneous values of mass per unit length and the straight line given by their mean value $\bar{x}$. The precise mathematical definition is:

$$U = \frac{1}{\bar{x}t} \int_0^t (x_n - \bar{x})\, dt .$$

As before, multiplication of either expression by 100 leads to an expression for $U\%$.

It can be shown mathematically that the two quantities CV and U are related by the expression

$$\frac{CV}{U} = \sqrt{\frac{\pi}{2}} \quad \text{or } 1.25$$

as long as a normal distribution exists in the individual values of mass per unit length. This is only true with fault-free fibre assemblies, so it is usual to prefer CV for expressing the results of evenness testing because a more precise integration can be achieved electronically than is the case for U.

2.1.3 Indices of Irregularity

The notion of an index to express irregularity appears to have been suggested originally by Spencer-Smith and Todd[14] and to have been developed separately by Martindale[15] and Huberty[16]. Briefly, an index of irregularity expresses the ratio between the measured irregularity and the so-called limiting irregularity of an ideal yarn. The manner in which irregularity is assessed can lead to different ways of expressing the index.

In calculating the limiting irregularity, the assumption is made that, in the ideal case, fibre distribution in a yarn is completely random and a practical yarn can never improve upon this situation. Thus, the measured irregularity will be an indication of the extent to which fibre distribution falls short of complete randomness. If all fibres are uniform in cross-sectional size, it can be shown mathematically that the limiting, or minimum, value of irregularity, expressed in terms of CV, is given by:

$$CV_{lim} = \frac{1}{\sqrt{n}} \quad \text{or } CV_{lim}\% = \frac{100}{\sqrt{n}} .$$

This expression also assumes a Poisson distribution in the values around n, the mean number of fibres in the yarn cross-section, a situation that need not necessarily exist in practice. With these two assumptions, however, an index of irregularity, K, as proposed by Huberty[16], can be derived such that:

$$\mathrm{CV} = \frac{K}{\sqrt{n}}\,.$$

Martindale's treatment extends this work on the assumption that, for a practical yarn, variations in linear density of the fibre must be taken into account and modifies the formula for limiting CV according to the equation:

$$\mathrm{CV}_{\mathrm{lim}} = \frac{100\sqrt{1 + 0.00004V_{\mathrm{D}}^{2}}}{\sqrt{n}}\,,$$

an expression that yields typical values for K of 106 for cotton, 112 for wool, and 104 for synthetic-staple-fibre yarns[17].

Dyson[18] proposes an extension of this simple theory, with some account taken of the fibre configuration in the strand. He assumes that both fibre fineness and fibre extent exhibit variability independently of one another and that the additional variability in effective fibre linear density can thus be taken into consideration. Using different mathematical models, in which particular assumptions concerning the distribution of fibre extents are made, he derives three equations, as follows:

$$\text{(a) } \mathrm{CV}_{\mathrm{l}}\sqrt{N} = \frac{100}{\sqrt{k}}\,;$$

$$\text{(b) } \mathrm{CV}_{\mathrm{l}}\sqrt{N} = \frac{100}{\sqrt{k}}\left\{1 + 0.35^{2} + \frac{(1 + k)^{2}}{3k}\right\}^{1/2};$$

and

$$\text{(c) } \mathrm{CV}_{\mathrm{l}}\sqrt{N} = \frac{100}{\sqrt{k}}\left\{1 + 0.35^{2} + \frac{(1 + k)^{2}}{k\sqrt{3}}\right\}^{1/2};$$

He then points out that an index of irregularity derived from the third of these equations provides a closer approximation to practical results than does the more traditional expression.

Wegener and Ehrler[19], using computer-simulation techniques, show that the index of irregularity is strongly dependent on both the fibre-end distribution and the coefficient of variation of the fibre-length distribution, though the type of distribution existing in either case has no effect. The same authors[20] also cast doubt on the validity of the use of the irregularity index, on the grounds that contemporary theories ignore fibre-end distribution.

Ratnam, Seshan, and Govindarajulu[21] publish practical results that also cast doubt on the usefulness of an index of irregularity. They derive values of K for a number of cotton yarns, spun under the same conditions from raw materials of different quality, and discover a wide variation in results. They note a trend for lower-quality cottons to produce yarns with consistently higher irregularity and suggest the use of a new type of index, derived as the intercept on the graph relating the slope of the draft–variance line to the count of the roving hank from which the yarn is spun. This intercept, a, is shown to be reasonably independent of both yarn count and yarn quality (i.e. fibre length). In theory, there appears to be no reason why the same procedure should not be applied to fibres other than cotton, but the authors do not yet seem to have taken this potentially useful step.

Wegener[22] examines work from several literature sources in an attempt to derive a total-variance coefficient for one-component fibre assemblies. He notes the wide discrepancy in published values of K for ten materials and shows that, at least for open-end-spun yarns, the concept of limiting irregularity is not a feasible one.

Other authors, however, disagree with these pessimistic views of the usefulness of an index of irregularity. Zeidman[23], accepting the fact that there is a dependence on irregularities of fibre fineness, length variation, and array, nevertheless finds the concept useful in contributing to more precise localization of sources of irregularity. Krause and Soliman[24] use an index measurement to show that open-end-spun yarns have a lower limiting irregularity than was formerly accepted. Silarova[25] uses a new statistical treatment to derive an irregularity index for wet-spun linen yarns. Linhart[26] suggests that Huberty's original hypothesis can be extended by the use of modern statistical theory and that a more precise (and fundamentally sound) method of measuring irregularity can thus be devised. Privalov and Truevtsev[27] propose a new, generalized equation for obtaining the theoretical coefficient of variation, taking into account fibre arrangement (particularly straightness and the presence of 'hooks'), the length of the yarn elements used in determining irregularity, and the influence of fibre length. Grosberg[28] uses an index of irregularity to demonstrate a marked correlation between yarn irregularity and mean fibre length. He points out that, by using the relationship, predictions can be made of the yarn irregularity likely to result when fibres of a given length are spun into yarns of any particular count.

2.1.4 The Exceeding Frequency

The final single-figure method of describing evenness, the exceeding frequency, was first suggested by Wegener and Hoth[29]. The value is defined as the frequency, f, with which a particular linear density is exceeded in a unit of yarn length and is given by:

$$f = A/L,$$

where A is the number of times that a specified value of CV% is exceeded in a given length, L, of yarn. The value of f is derived for a variety of situations by computer-simulation techniques, and theoretical curves are drawn in which the exceeding frequency is plotted against the number of fibre ends and the number of fibres in a yarn cross-section. Both curves exhibit approximately a Poisson distribution.

When the results are applied to a practical fibre assembly, fibre–fibre friction and periodicity are shown to modify the situation, and a number of equations are derived to relate exceeding frequency with other parameters. These are applied to four different yarns, by using each of the different formulae, and the fit of the hypothetical curves to practical values is compared.

Wegener and Vogt[30] extend the work to show that the presence of significantly thicker places can readily be detected by using the Uster Evenness Tester. The thick places are again located according to a Poisson distribution, and, with increased threshold value, the distribution of the exceeding frequency approaches that of the thick places actually present. The length distribution of yarn portions free from thick places is calculated and shown to be defined by an exponential function. It is thus possible to establish quality-assessment formulae to predict the frequency and average mass of thick places for any given deviation in linear density.

A further practical assessment of the usefulness of the exceeding frequency is provided by Funder, Criese, and Heim[31], using linen yarns. They show that the number of thick places present has no effect on winding efficiency but obviously influences productivity if clearing is carried out. In weaving, the number of yarn breaks is related to the exceeding frequency, but in some non-linear (and undefined) manner. The authors claim that a classification of yarns by thick-place count can be used reliably to predict the ease of subsequent processing and the quality of a yarn.

2.2 Correlation Methods

The autocorrelation function, or correlogram, is defined as the mathematical function relating the correlation coefficient between two sets of measurements at points separated by a distance L to the value of L. It is widely used for analysing irregularly oscillating curves, and its application to yarn-evenness work was first described in detail by Cox and Townsend[32]. These authors define the function, point out that it can be used to derive variance–length curves (see Section 2.4), and carry out a detailed examination of several yarns by using the technique. They show also that prediction of the autocorrelation function, $\rho(L)$, from the fibre-length distribution is feasible, the accuracy of such prediction being greater the nearer the distribution is to a random one. In addition, calculations of the variance–length relations, $B(L)$ and $V(L)$, from $\rho(L)$ are attempted for three yarns at a range of lengths. Comparison with results obtained by the gravimetric technique indicates modest agreement between the two methods, the differences being explained by a departure from randomness in the fibre-length distribution. An important conclusion drawn is the fact that a single measure is not sufficient to assess all features of the irregularity of a yarn, a finding that is currently widely accepted and explains the lack of interest in indices of irregularity as useful descriptors of evenness.

The use and properties of the autocorrelation function are examined in detail in a series of articles by Wegener and Feier[33–39]. In the first of these[33], various methods of deriving and determining theoretical or practical correlograms are described, and the usefulness of the function is demonstrated by analysing the mass variations along three yarns. It is pointed out that, in contrast to the spectrum function (see Section 2.3), mass variations associated with phase shifts in the periodicity can be analysed. One weakness of the technique, however, is its inability to permit comparison of scatter between results derived from different test sites. The second paper[34] is a short one, dealing from a purely theoretical viewpoint with the technique for describing any time function by means of the autocorrelation function, and some indication is given of the usefulness of correlograms in a variety of applications, including that of yarn evenness. A simple block-circuit diagram of a system suitable for analytical procedures is provided.

The third paper[35] deals once again with the properties and derivation of the autocorrelation function from a theoretical point of view but also provides information of practical interest. The function is defined mathematically as:

$$A(T) = \lim_{t \to \infty} \frac{1}{t} \int_{t_1}^{t_1 + t} y(t \text{[redacted]}$$

where $A(T)$ is the autocorrelation function, with respe[redacted] time, of a var[redacted]ng quantity T, t_1 the integration time measured from a starting time t, and $y($[redacted] to be analysed. It is shown mathematically that one may then derive the pr[redacted]:

$$A(T) = \frac{A_0^2}{4} + \frac{1}{2} \sum_{n=1}^{\infty} A_n^2 \cos n\bar{\omega}T \ ,$$

where A_0 is a constant associated with the signal, n the running value, A_n the amplitude of the particular frequency component, and $\bar{\omega}$ the angular frequency.

Illustrations of the results derived by analysis of several different types of input signal, of varying degrees of complexity, are then given to illustrate the versatility of the technique. Finally, a review of the practical work of other authors who have reported methods of drawing correlograms is presented, electronic and optical techniques both being represented. As is always the case in Professor Wegener's work, a comprehensive list of literature sources is also included.

Wegener and Feier[36] next investigate the effect of a variation in the distribution of fibre ends, fibre length, and fibre cross-section on the autocorrelation function. Simulated model fibre assemblies are used, and variation in any one of the three quantities is shown to exert a slight, but significant, influence on the correlogram. When the work is extended to actual fibre curves[37], it becomes obvious that the assumptions made in deriving simulated curves are inadequate. Two computer techniques for deriving the correlograms are used, in conjunction with an Uster Tester, and a brief description of the experimental method is provided. When practical and simulated results are compared, it is seen that a steeper fall-off in autocorrelation function occurs at lower values of correlation displacement than that predicted by simulation techniques. In addition, the 'standardizing value' used by the authors is unexpectedly higher for the practical results. It is thus evident that real fibre assemblies are more irregular (as defined by the usual statistical measures or by time-series analysis) than are the ones simulated by Poisson-distribution model techniques. The implications of this fact, with regard to the effects of fibre type or length, twist, crimp, and hairiness on autocorrelation functions of both types, are then discussed briefly.

The next article of the series[38] is devoted to practical results, comparisons being drawn between the autocorrelation functions of four yarns with widely differing profiles. As might be expected, knot and loop yarns differ significantly from slub and spiral-slub yarns, as may be seen in Fig. 1, taken from two figures given in the paper.

Possible sources of error in deriving a correlogram are the subject of a further publication by the same two authors[39]. They are concerned mainly with mathematical (rather than equipment) sources resulting from abnormal distribution of fibres within a yarn and from imprecision in estimates of the true mean value of mass per unit length.

One other paper worthy of mention in the context of correlation techniques is that by Privalov[40]. He points out that, in constructing models of ideal fibre assemblies, when a random fibre-length distribution is assumed, the effects of fibre–fibre friction during the manipulation occurring in spinning are ignored. He suggests that complex Markovian processes (or auto-regression techniques) must be used if irregularity is to be analysed successfully. He illustrates the point by examining the variations present in a regular cotton yarn and provides information enabling standardization of the autocorrelation function to be set more accurately.

In more recent years, correlation methods have diminished in popularity among research workers, partly because of the difficulties involved in obtaining accurate measurements and partly because variance–length curves, related to them and much easier to obtain, contain visually more information and are less complex to interpret. These curves are to be discussed in due course.

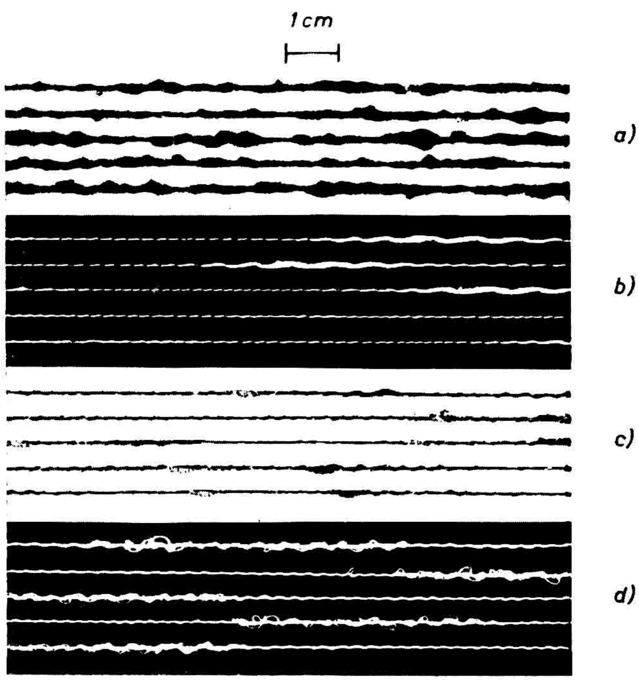

Fig. 1
Typical fancy yarns (above) and their corresponding autocorrelation functions (opposite): *(a)* slub yarn, *(b)* spiral-slub yarn, *(c)* knot yarn, *(d)* loop yarn

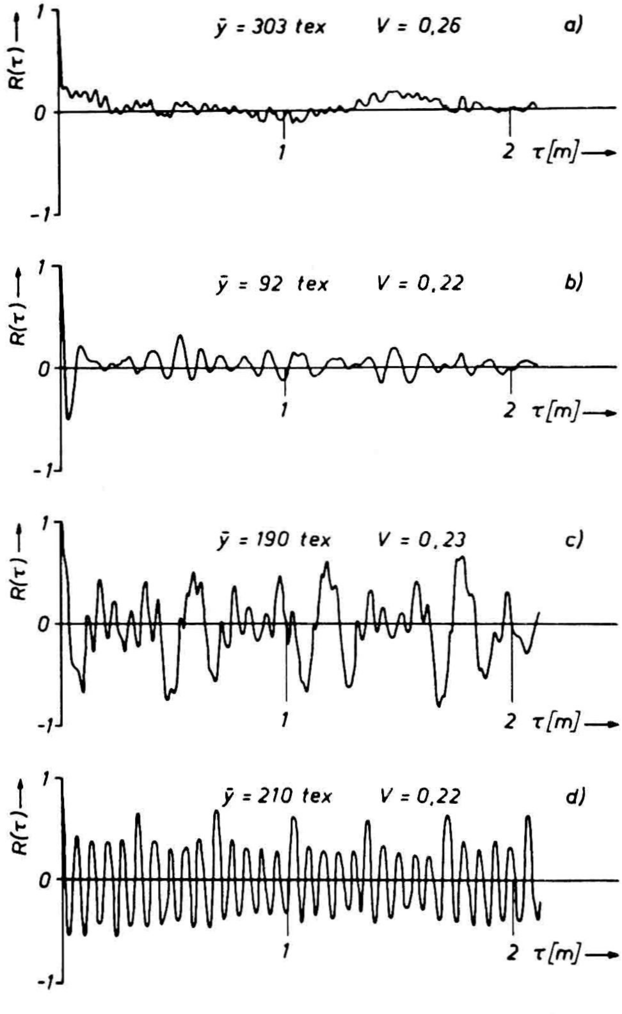

Fig. 1

2.3 Spectral Methods

An alternative approach to the problem of identifying periodic variations in textile materials is to use the technique of spectral analysis. In this procedure, the variation in mass per unit length is computed as a function of some variable other than time or length. Wegener and Guse[41] describe several ways of presenting a spectrum and several methods of experimental spectral analysis and then study the statistical validity of the various techniques. The most usual variable is one of frequency or, more commonly, wavelength. Thus, in spectral methods normally encountered, the mass variation is plotted as a function of wavelength. The well-known Uster spectrogram is a typical example of the results obtained by such a technique.

The major advantage of a spectrogram is its ability to display clearly any periodic mass variations. It is particularly useful when two or more variations are present in a single fibre assembly, since one or more of them can easily be masked when the methods described earlier in this section are used. Disadvantages of the spectrogram include the cost of providing a sufficient number of electronic filters to give analytical precision, the difficulty of establishing an exact meaning to the height of any particular peak, and the fact that it can yield results only up to a wavelength limit set by the filters (40 m in the Uster Tester), with no possibility of extension in an examination of long-term irregularity. Nevertheless, some useful work based on spectral analysis is reported in the literature.

Wegener and Guse[42] carry out spectral analysis on a simulated fibre assembly with the aid of computer techniques and describe in some detail the density spectrum of assemblies with random fibre arrangement. In a later paper[43], the same authors extend their work to study the relationship between the structure of a sliver and its 'output-density spectrum'. They conclude that the maximum amplitude is independent of the fibre-length distribution when the fibre-end distribution per unit length follows a Poisson law but falls, when the CV of fibre-end distribution is greater than that expected by a Poisson law, as the CV of fibre-length distribution increases. Since real yarns always follow the latter course, the authors conclude that, in such cases, a yarn with variable staple length, under the correct production conditions, can be made more regular than one with constant staple length, a result contrary to the usual expectations. They provide an expression:

$$S^2\ (lg\ \lambda) = \frac{ln\ 10}{2\pi^2\ n\bar{l}} \left\{ \lambda - \lambda \cos\left(\frac{2\pi\bar{l}}{\lambda}\right) + \frac{2\pi^2\ \bar{l}^2}{\lambda}\ V_{FL}{}^2 \cos\left(\frac{2\pi\ \bar{l}}{\lambda}\right)\right\}$$

to relate the maximum position of the wavelength λ to the mean fibre length $\bar{l}$ and the CV of fibre-length distribution, V_{FL}.

Kirschner, Petiteau, and Schutz[44] study the transverse and longitudinal irregularity of fibre assemblies by Fourier analysis and begin with a determination of the spectra obtained from various theoretical distribution models. They then use their results to examine in more detail the interpretation of real spectrograms in terms of these models. Narasimham, Garesh, and Kothari[45] divide yarn irregularity into three separate components, the variations of periodic, random, and quasiperiodic types. They carry out spectral analysis of each of the three types and use their results (in comparison with yarn spectra) to propose models for the arrangement of fibres in these yarns. Ruedi[46] interprets spectra from Fourier analysis of individual-test-point data and uses his results to illustrate the effects of random errors. De Castellar[47] also carries out a Fourier analysis to determine a spectral-density function $h(\ )$ and comments on the similarities between diagrams obtained for thickness, cross-section, and linear density. She suggests that an approximation can be made of the spectral-density function over an infinite interval and that such a spectral analysis is useful in indicating sliver or yarn structures.

2.4 Variance–Length Relations

The most widely used contemporary method of expressing the evenness present in a yarn comprehensively is by means of a variance–length curve, and the development of this device over the past decades is interesting to recount. Pioneer work in the area was carried out by Townsend and Cox[48], who used existing mathematical treatments devised originally to deal with economic and meteorological analyses. In addition, they integrated work carried out by earlier authors, who had considered various aspects of the relation between mass variance and the length of yarn measured. Their original treatment is based on the square of the coefficient of variation, $(CV)^2$, which they define as the mean standardized variance, $V(L)$, within random samples of length L of a yarn. They then define a function $B(L)$ as the standardized variance between the mean mass values of lengths of yarn L and derive the relation:

$$V(L) + B(L) = V(\infty),$$

where $V(\infty)$ is the over-all, or total, variance.

For a typical (ideal) yarn, the shape of the curves relating the three functions to the test length is illustrated in Fig. 2. Total variance, $V(\infty)$, is fixed and thus independent of the length of yarn measured, but the other two variance–length relations must obviously be variable. As the yarn test length increases, the variance within the length will clearly increase, for the simple reason that

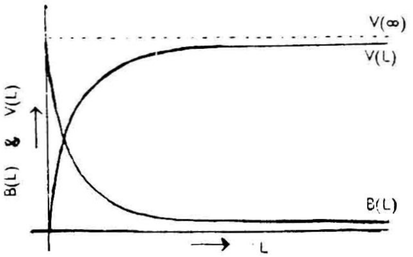

Fig. 2
Shape of curves relating *V(L)* and *B(L)* to test length for ideal yarn

additional length introduces more opportunity for variation to arise. Eventually, however, all possible variations will be contained in a given piece of sufficient length, so that any increase in length will increase only slightly, if at all, the possibility of additional variance being present. Thus, the *V(L)* curve will begin at the origin (since there is no variance within a yarn of zero length) and will rise, steeply at first and then more gradually, to an asymptotic value of $V(\infty)$.

Conversely, the *B(L)* curve will have a high value at short lengths, since there is more likelihood of a variation between short lengths than between longer ones. As length increases, the likelihood that two pieces will have the same mass also increases as a result of the averaging effect of a larger number of fluctuations of mass in any one sample of yarn. The *B(L)* curve therefore has an initial value of $B(\infty)$ at zero length and then falls, rapidly at first and more slowly subsequently, to an asymptotic value of zero at very long lengths.

The authors proceed to describe several methods of deriving the two curves and point out the tedious nature of the operation and the need for large quantities of data for acceptable precision. In addition, they provide a formula for obtaining the *V(L)* curve by integration from the correlogram.

It was quickly realized that the *B(L)* curve is the more useful one of the two for expressing yarn evenness. It is a more sensitive measure over the region where variation is most likely to exist and is, in addition, easier to establish by the basic method of cutting and weighing pieces of yarn. Later authors therefore devote their attention almost exclusively to this curve. Naturally, since the two curves are mathematically related by the simple equation already quoted, it is theoretically possible to calculate one from the other if a value of $V(\infty)$ can be established; this point will be taken up in a subsequent section.

Olerup[49] presents a method of calculating mathematically each point on the *B(L)* curve of an ideal sliver and establishes the fact that the curve is a logarithmic one except at very low values of length, when it tends to a constant value termed $B(0)$. Breny[50] extends the work to yarns and gives a complex formula by which the value of $B(L)/B(0)$ can be calculated, for any length L, from a knowledge of the length distribution of fibres in the yarn. Van Zwet[51] presents a cumulative method of deriving points so that fewer determinations of mass are needed, while Hannah and Rodden[52] consider the case where restricted variation in fibre position is assumed in arriving at a yarn model.

Wegener, in conjunction with other authors[53–65], has carried out a considerable amount of work in the area of yarn evenness. He shows, with Probst[53], that there is a close resemblance between the *B(L)* curve for mass variation and the ‘length-variation characteristic’ of twist. Wegener and Peuker[54] describe how a variance–length curve is established and, in later work[55], derive a relationship between the *B(L)* curve, the fibre-length distribution, and an ‘external’ unevenness characteristic, *CB(F)*, derived from variations in surface area. Wegener and Hoth[56] give more detailed information concerning this *CB(F)* characteristic and, in a later paper[57], describe a general method for calculating ideal variance–length functions. The same authors[58] elaborate on this method in subsequent work and provide a series of tables to assist in the task of carrying out calculations. Wegener and Rosemann[59] compare the statistical definition of the variance–length curves with a mathematical one based on the principle of continuous integration. The two treatments are shown to give equivalent results, so that curves derived by electronic integration from yarn-linear-density traces may be regarded as accurate. The same authors, in a later paper[60], use rectangular and sinusoidal waveforms to simulate periodic variation and variance, both within and between lengths, to the test length. They find a marked difference, at short test lengths, between the curves resulting from the two types of waveform and deduce that textile-fibre assemblies exhibit behaviour that corresponds to a constant material density. Wegener and Rosemann[61] then direct their attention to this short-length region and examine more carefully the mathematical methods of describing variance–length in this area. They find that, at small values of *L*, there are slight, but significant, differences between results of the two treatments and, in a subsequent paper[62], demonstrate that Fourier analysis may be used with some benefit in deriving length-variation curves.

Wegener and Ehrler[63] use computer-simulation techniques to derive ideal variance–length curves and extend the work, in later papers[64, 65], to include a consideration of actual fibre assemblies. The effect of fibre-length-distribution curves is examined in some detail in the first of these[64], while the second one[65] illustrates, by means of 'three-dimensional' graphs, the effect of fibre length and its distribution on the *B(L)* curve. In addition, the usefulness of *K(L)* values, derived by an extension of the principle of index of irregularity considered in Section 2.1, is discussed in some detail.

Vroomen[66] presents theoretical points regarding the derivation of *B(L)* curves. He defines it in mathematical terms, discusses the manner in which the asymptotic value of zero is approached, and examines the validity of calculating the shape of the curve from a knowledge of the length distribution of fibres. He suggests that the Evenmeter can be used to accelerate the process of deriving the curve, an idea that is examined in more detail by Francise[67]. The two authors then jointly report work in which comparisons of the electronic derivation of a *B(L)* curve and gravimetric techniques are performed[68]. Results of the two procedures are sufficiently close to permit the Evenmeter to be used in obtaining *B(L)* curves, a point that will be examined further in Section 4.

Two final papers are of interest in the context of this topic. Raw[69] and Moon[70] use probability theory to assess the irregularity of fibre assemblies. In the former case, uniform yarns and slivers are assumed in the model, and a variance–length curve is established by deriving two random variables. Limiting irregularity is calculated and shown to increase with both fibre and yarn count but to be independent of fibre length. Moon's findings are similar, and he also shows that this method of deriving the *B(L)* curve is mathematically compatible with the technique of using a time series.

2.5 Comparative Studies

In view of the number of methods available for determining yarn evenness, it is hardly surprising that differences of opinion exist in the literature concerning the optimum technique. There is general agreement that the basic method of cutting and weighing many specimens of yarn, at a range of fixed lengths, is the one that should be regarded as standard, but there is also a recognition that the tedium and the inherent lack of precision in this method make it unsuitable for routine use. In consequence, all techniques intended for an analysis of evenness are usually tested initially against this fundamental method to establish their validity.

An additional consideration, however, is the amount of information that any given technique can convey, together with the ease of interpretation of this information, in conjunction with the difficulty of incorporating the information accurately. Once again, Wegener is a leading author in this area and, with other workers, has published an appreciable amount of work[71–75].