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YARN DIAMETER CHARACTERIZATION USING TWO ORTHOGONAL DIRECTIONS

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The most important parameters that are used to specify yarn quality are the linear density, structural features (e.g., twist, porosity), and fiber content. An example of a typical yarn configuration (Fig. 1a) shows that the yarn diameter is the distance between yarn contours and that irregularities (length and identification) are reported in terms of the mean yarn diameter. The detection of the number of faults in a yarn is used to provide a quality rating of the yarn. There are three main kinds of yarn faults, classified as (Fig. 1b): thin places: a decrease in the mass during a short length (4 mm); thick places: an increase in the mass, and lasting more than 4 mm; neps: a huge amount of yarn mass (equal or greater than 100%) in a short length (typically from 1 to 4 mm).[1–5] As Fig. 1 suggests, there is a direct relationship between the variation of yarn mass and the yarn's diameter. The yarn linear mass is generally expressed in tex units which represents the mass of yarn (g) over a 1 km length.

In addition to faults, another important feature that greatly influences the appearance of fabrics is the level of hairiness of a yarn. Hairiness is the result of released fibers over the strand. Figure 2 presents an example of yarn hairiness in an 49.2 tex 100% cotton yarn, imaged with an electron microscope using a magnification factor of 50×.[4–6] The measurements of yarn, hairiness, mass, and diameter allow the quantification of several statistical parameters that are significant in the quality of yarn characterization and of the fabrics produced from them.

Nowadays, to quantify diameter variations, commercial systems generally use optical methodologies.[7,8] The most commonly used modules are the diameter module of Uster Quantum-2,[9] the diameter module of Uster Tester 5,[10] and the Oasys from Zweigle.[11] These systems characterize the diameter of yarn by measuring the quantity of light from a red/green source blocked by the yarn. The signal received by the final sensor is proportional to the diameter of the yarn. Besides the above-referred systems, Keisokki-Laserspot determines the yarn diameter using a laser and a line array detector to characterize the light diffraction by the yarns.[12] In addition, another company, Lawson-Hemphill, uses an optical system (EIB) with a line scan camera, where the diameter is the distance between the pixels registering a signal at a user-set threshold level.[12] The Uster Tester 5 uses a two-dimensional system, whereas the others consider a one-dimensional system. The sample length measured by the Uster Quantum-2 is 3 mm, the Oasys-Zweigle is 2 mm, whereas in the Uster Tester 5, Keisokki-Laserspot, and Lawson-Hemphill EIB it is less than 1 mm.[9,12] The Uster Tester 5, two-dimensional high resolution, results from the fact that the measurement is used to represent three-dimensional diagrams and to reduce the influence of the yarn shape in measurements.[13]

None of the above-referenced commercial techniques eliminate signals due to yarn hairiness. Even the Keisokki-Laserspot can be influenced by the presence of some small hairiness components because it is completely based on light diffraction. The method used by the Lawson-Hemphill EIB lacks precision in the sense that the setting of the threshold values is somewhat arbitrary. There are faults that significantly vary the yarn diameter in both directions so that the yarn alignment must be accurate. In the Uster and Zweigle systems, some of the light source is blocked by the yarn hairiness so the precision of the yarn diameter measurement will suffer. In the Keisokki-Laserspot and Lawson-Hemphill EIB methods, the determination of diameter is also affected negatively by the fact that the hairiness always lies at the yarn edges. The inability of these systems to eliminate the influence of hairiness means that they generally report higher values for the yarn's diameter. As an alternative, we have used a coherent optical signal processing technique based on Fourier optics to characterize yarn diameter using a single projection.[13] In order to create a well-defined linear saturation zone with high directionally, a laser source was used, improving system resolution. The use of an incoherent light source will compromise all these assumptions.[13] By using a coherent optical signal processing technique, we can overcome the problem related to yarn hairiness, using a low-pass spatial filter in the Fourier plane. Previous studies showed that, using this system, a signal proportional to the yarn diameter is obtained.[13]

A full yarn characterization should require several different and simultaneous projections. However, considering that irregularities are randomly distributed over the yarn, there is a high probability that the irregularities will be uniformly distributed over a full rotation of the yarn on average. With this study, we verify that the results obtained using two orthogonal projections give essentially identical statistical results, implying that a single projection is sufficient for the correct determination of yarn diameter.

DEVELOPED YARN DIAMETER CHARACTERIZATION SYSTEM

The method developed to characterize yarn diameter along a single direction consists of a single transverse mode visible diode laser as a light emitter and a photodiode as a receiver, using a coherent optical signal processing technique based on Fourier optics.[6] Consider a collimated coherent plane wave that illuminates an object and then propagates through a lens toward its principle focal plane on the far side. Fourier optics implies that the electric field distribution in the focal plane of the lens is the Fourier transform of the field distribution in the object plane.[14] The lower spatial frequencies

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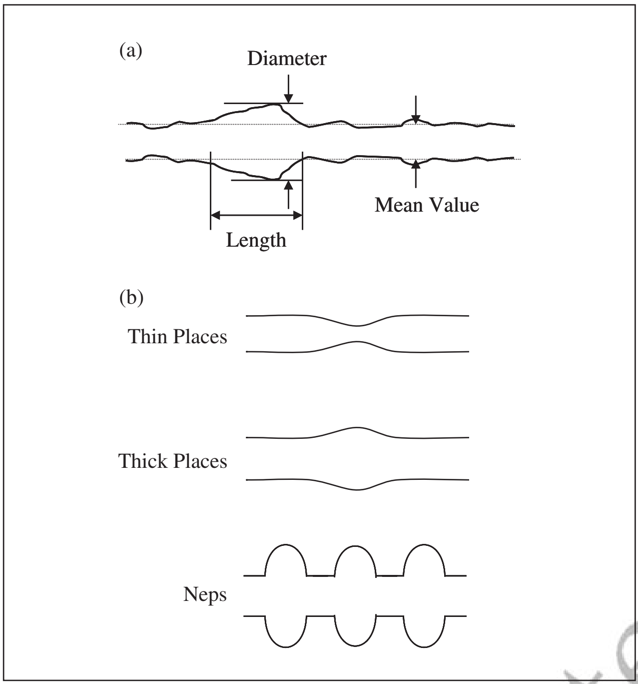

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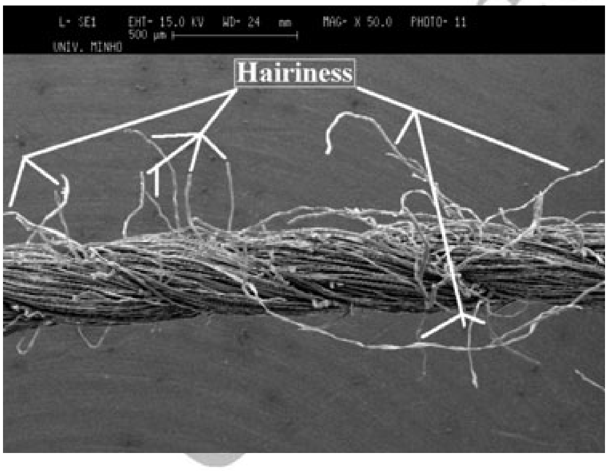

Fig. 2: Identification of yarn hairiness in an electron microscope photograph

of the image will be concentrated close to the optical axis, whereas the higher spatial frequencies will be located further from the optical axis. Mathematically, the field distribution in the principal focal plane of the lens will be given by the expression:

$$F\{g\} = \iint_{-\infty}^{\infty} g(x, y)e^{-j2\pi(v_x x + v_y y)}\mathrm{d}x\mathrm{d}y, \tag{1}$$

where $g(x,y)$ describes the field distribution in the object plane, V_x and V_y are the respective spatial frequencies (m^{-1}) along the x- and y-directions and j represents the imaginary plane coordinates. Variations in the electric field of the incident beam caused, for example, by a small object with a size d will, by diffraction, produce variations in the transmitted electric field with a characteristic spatial frequency given by $V \sim 1/d$. Within a paraxial approximation, the Fourier lens will then focus this pattern to a region centered on the optical axis with size of order R (m), given by expression:

$$R \sim \frac{f\lambda}{d}, \tag{2}$$

where λ is wavelength (m) and f is the focal distance (m) of the Fourier lens. Depending on the exact geometry of the object, a numerical factor of order unity will multiply the term on the right; for example, for the case of a circular object the corresponding factor is 1.22. Sharp transitions from light to dark in the object plane will result in high spatial frequencies, whereas the nearly uniform background illumination only possesses very low spatial frequencies.

A measurement that highlights the hairiness of the yarn can be accomplished by placing a small round opaque filter (high-pass filter) centered on the optical axis in the Fourier plane. This blocks the low-frequency background information, whereas the information about the sharp transitions from light to dark that occur at the yarn boundaries and protruding fibers (hairiness) can pass through. Alternatively, by inserting a low-pass optical filter that allows only light close to the optical axis in the Fourier plane to propagate further, only the information about the shadow of the yarn core will be transmitted. When imaged by a second lens, this low-pass filter setup results in the yarn core shadow on a bright nearly uniform background. The amount of light blocked by the yarn core is proportional to the yarn diameter. This information is converted by a photodiode into a proportional current intensity.[6,13]

Consider for the moment a full 360° rotation of a yarn with a thick place irregularity about its axis when sampled by a single projection perpendicular to its axis. This would result in a signal similar to that shown in Fig. 3. Assuming that the laser light is incident from the left along the horizontal direction and considering a top view, the maximum signal is obtained for positions referenced by 1, 3, and 5. The overall signal would be well described by a constant modulated by the absolute value of the cosine, being the projection of the yarn irregularity onto the direction of the incident light. This signal distribution is valid for the yarn irregularities characterization regardless of the yarn manufacturing process and type. In the absence of irregularities, a flat constant signal would be obtained. If several thick places were positioned over the yarn with different orientations, several protruding deviations would be obtained corresponding to a superposition of sinusoidal modulated patterns.

The average signal modulation obtained using a single projection (S_1), corresponds to roughly $2/\pi$ times the maximum signal modulation,[15] as

$$\langle|\cos\theta|\rangle = \frac{2}{\pi}\int_0^{\pi/2}\cos\theta\,\mathrm{d}\theta = \frac{2}{\pi}.$$

This implies that the total irregularity, (S_t), would be in fact $\pi/2$ times greater than the average amount of irregularity

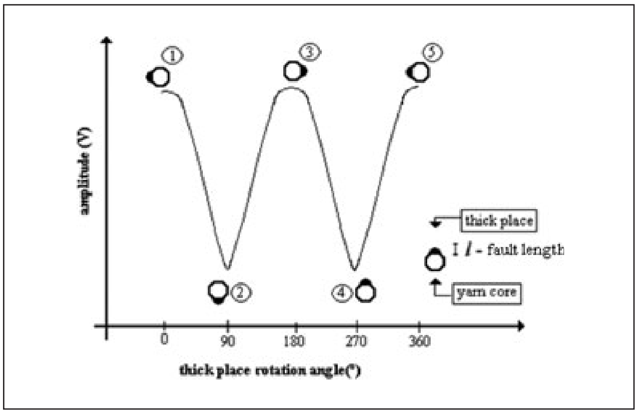

Fig. 3: The signal that would be observed as a thick place is rotated 360° about the yarn axis

$\langle S \rangle$ obtained using a single projection along an arbitrary direction.

If a second diameter measurement is realized along an orthogonal direction, the same signal shifted by 90° with respect to that of Fig. 3 would be obtained.[15] As yarn irregularities should be randomly distributed over the length of the yarn, a roughly equal distribution over 360° would be expected for the high number of samples traditionally used in a yarn test. In order to explore the validity of this assumption, a double coherent imaging setup was developed to characterize the yarn diameter simultaneously along two orthogonal directions.

EXPERIMENTAL CONFIGURATION

To measure yarn diameter, an optical and an electronic setup was used. The optical setup, as shown in Fig. 4, uses a diode AQ5 laser illumination source (Eudyna FLD6A2TK) that emits light at 685 ± 10 nm in both a single transverse and single longitudinal mode with an especially low aspect ratio of 1.3. Emitting in a single longitudinal mode, the coherence length of the laser light is expected to be greater than several meters. The light from this laser was collimated using a single plano-convex lens of 40 mm focal length (L1). After illuminating the sample under study (O), the light passes through a 60 mm focal length, 50 mm diameter plano-convex lens (L2) used to obtain a spatial Fourier transform of the object in its principal focal plane. A roughly 1 mm diameter circular aperture (F) was placed in the Fourier plane, blocking all spatial frequencies above 10 mm^{-1}, corresponding to a characteristic size of 100 μm or less in the object plane. Fortunately, there is a good distinction in the characteristic length of the yarns scales. Textile yarns typically have diameters ranging from a few hundreds of micrometers up to millimeters, whereas the small hairs protruding from the yarn are single fibers with diameters typically less than 10 μm. The filter is chosen to block the information due to the small fibers, while maintaining the information due to the light blocked by the central yarn core. A third plano-convex lens of 60 mm focal length (L3) is used to form a final filtered image. In this setup, all lenses have a broadband antireflective coating. In addition, an interference filter centered at 680 nm with a bandpass (full width at half maximum) of 10 nm and a peak transmission of 50% (Thorlabs FB680-10) was placed directly in front of the detector to limit the AQ6 amount of stray ambient light detected.[15] Figure 5 presents an example of an image resulting from the application of a low-pass spatial filter[13] where it is observed that there is virtually no hairiness present, only the yarn core and the light not blocked by the sample are visible.

The photocurrent from each photodiode was converted into a voltage by a transimpedance amplifier characterized by a bandwidth of 1 MHz, an offset voltage of ±10 μV, a noise level less than 10 mV, and a noise equivalent power (NEP) of 3.1×10^{-15} W/Hz$^{1/2}$. The output power of the lasers during measurements has variations inferior to 1%. The goal of the electronic hardware is to obtain a voltage proportional to the brightness of the final image.[6] The output of a transimpedance amplifier[16] is read by the USB-6251 data acquisition board (DAQ) from National Instruments.[17] Some of the main features of the USB-6251 DAQ board are 16 bit of resolution, maximum acquisition rate of 1.25 MHz, maximum range of ±10 V and a ±1 least significant bit (LSB).[13,15]

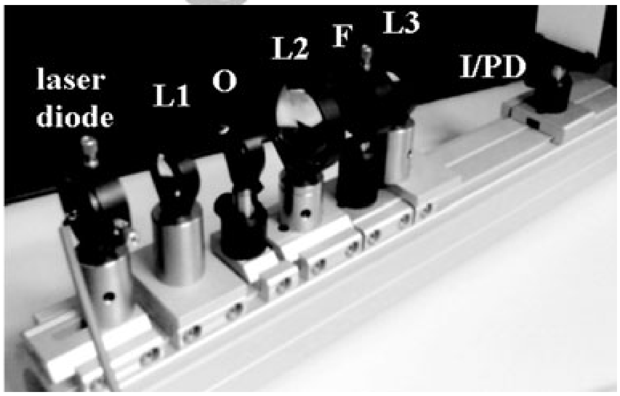

Fig. 4: Optical system used to measure yarn diameter along a single projection

Fig. 5: Example of an image resulting from coherent optical signal processing

To build the optical hardware to characterize the diameter along the orthogonal projection, we have used the same type of optical elements. However, because of equipment limitations, the elements in the second optical arm have different characteristics; the lenses used have slightly different focal lengths and the laser source operates at a different wavelength and power. Nonetheless, the operation principal is identical, while the associated electronic hardware is reproduced exactly. Moreover, to ensure that the beam area incident on the photodiode is precisely the same, we built two similar windows with 5 mm height (final beam area of 5 mm × 10 mm) and placed them over the active area of the photodiodes. To obtain approximately the same output signal amplitude in both setups, the gains used in the transimpedance amplifiers needed to be adjusted differently for each setup, compensating for the slight differences in the optical hardware and light sources. Light source 1 is a helium–neon (HeNe) laser with a wavelength of 632.8 nm, with a polarization contrast of more than 100:1 and light source 2 is a laser diode with a wavelength of approximately 685 nm, as referred previously, with a polarization contrast of better than 100:1. A schematic of the overall optical hardware setup for two directions is shown in Fig. 6.[13,15] The system designed is characterized by a sensitivity of 0.052 V/mm^2 with an error less than 2% and an error standard deviation (SD) less than 5%, enabling the determination of very low variations of yarn diameter.[13]

EXPERIMENTAL RESULTS

Several tests were performed in a single direction and in orthogonal directions to compare results.

Single Direction for a 360° Characterization

To analyze the results obtained for irregularities in a full projection analysis (360°) using a single photodiode, several samples of four different yarns were used. In each case, the same yarn was sampled at 10 different locations, while at each sample location the yarn was rotated by 360°. The important experimental information is the amount of light blocked by each yarn. This is calculated by subtracting the signal obtained with the yarn present from the signal value without the yarn present. Of course, higher diameter yarns block a higher amount of signal. Table 1 presents the linear mass for each yarn tested. In percentage, the linear mass is directly proportional to the yarn diameter, so the thicker yarn is 295 g/km and the thinner yarn is 4.2 g/km. Table 1 also presents the average and the standard deviation (SD) of the results obtained for each of the 10 yarn samples over a full 360° rotation. For these yarns, the irregularity level

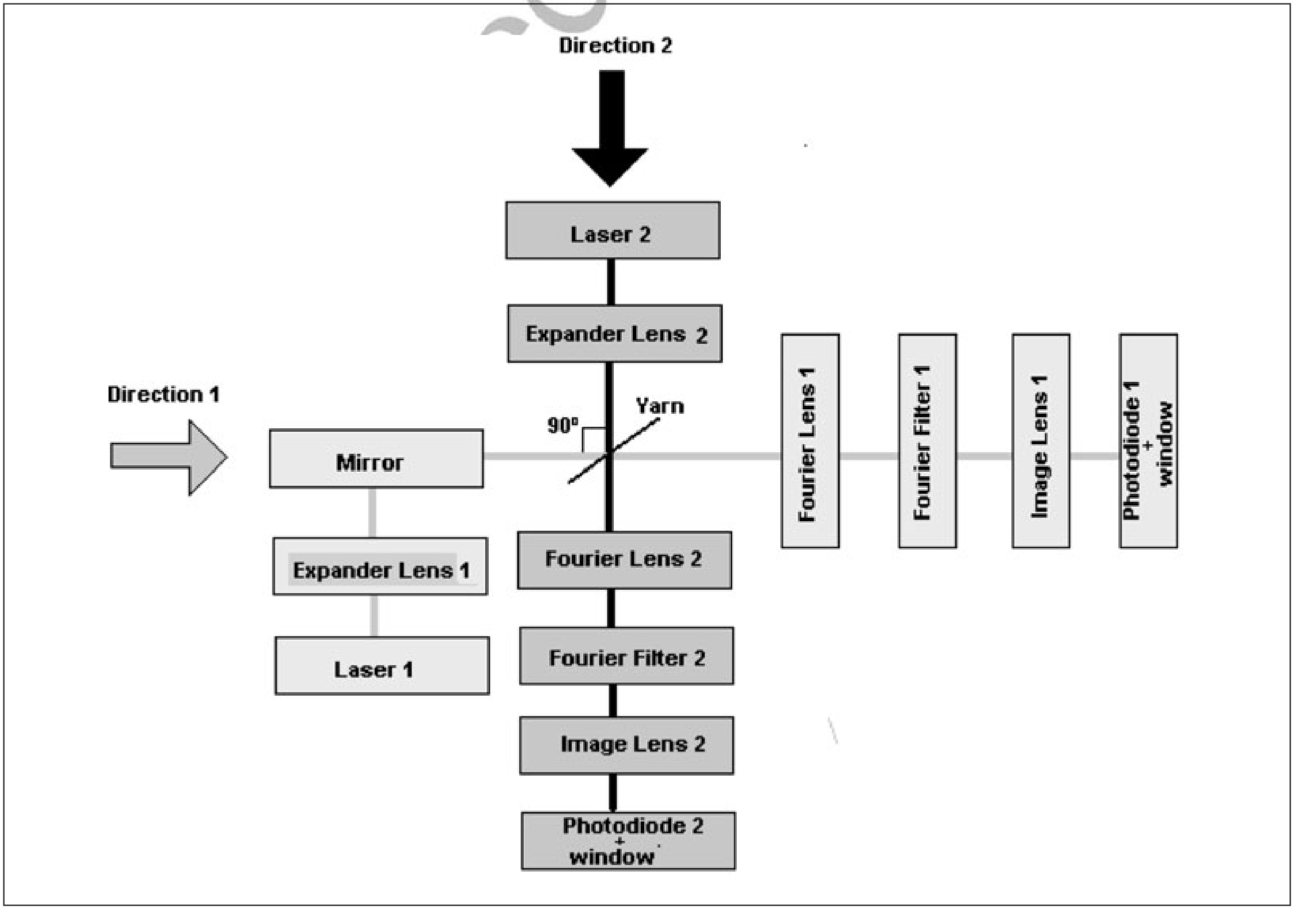

Fig. 6: Experimental configuration of an orthogonal yarn diameter analysis

Table 1—Statistical analysis for each yarn sample over a full 360° rotation

SAMPLE NO	YARN LINEAR MASS (g/km)			
	295 $\bar{x} \pm$ SD (V)	62 $\bar{x} \pm$ SD (V)	49.2 $\bar{x} \pm$ SD (V)	4.2 $\bar{x} \pm$ SD (V)
1	0.76 ± 0.0097	0.31 ± 0.0107	0.22 ± 0.0084	0.09 ± 0.0041
2	0.85 ± 0.0223	0.25 ± 0.0092	0.21 ± 0.0069	0.09 ± 0.0049
3	0.76 ± 0.0344	0.37 ± 0.0125	0.21 ± 0.0058	0.08 ± 0.0051
4	0.71 ± 0.0243	0.42 ± 0.0142	0.23 ± 0.0119	0.10 ± 0.0048
5	0.62 ± 0.0154	0.34 ± 0.0165	0.18 ± 0.0048	0.11 ± 0.0047
6	0.69 ± 0.0492	0.38 ± 0.0165	0.19 ± 0.0062	0.11 ± 0.0042
7	0.69 ± 0.0378	0.33 ± 0.0114	0.21 ± 0.0046	0.11 ± 0.0043
8	0.71 ± 0.0310	0.13 ± 0.0245	0.20 ± 0.0056	0.11 ± 0.0056
9	0.78 ± 0.0251	0.34 ± 0.0105	0.19 ± 0.0083	0.09 ± 0.0043
10	0.66 ± 0.0176	0.50 ± 0.0324	0.20 ± 0.0047	0.10 ± 0.0042

Table 2—Statistical analysis for samples corresponding to the presence or not of faults

YARN LINEAR MASS (g/km)	295	49.2	295	62	4.2
Sample no	3	2	6	8	1
Sample average (V)	0.760	0.210	0.690	0.130	0.099
Yarn average (V)	0.723	0.204	0.723	0.337	0.099
Diameter variation over average (%)	+5.12	+2.94	−4.56	−61.42	0
SD sample average (%)	2.668	0.69	4.92	2.45	0.48
Yarn SD average (%)	3.44	0.672	2.669	1.584	0.462
Pattern deviation (%)	28.94	2.68	84.41	54.67	3.90
Detected fault	Thick place	Thick place	Thin place	Thin place	None

is strongly correlated to the linear mass of the yarn; the 4.2 g/km yarn is the most regular,[18] whereas the 295 g/km is more irregular.[19] Consequently, the lowest SD amplitude was obtained for the 4.2 g/km yarn followed by the 49.2 and the 62 g/km yarns. The highest SD amplitude is obtained for the 295 g/km yarn. This situation can be explained by the fact that a higher linear mass yarn has more fibers per unit length and subsequently a higher probability of having irregularities. As expected, the average signal level associated with each yarn is highly correlated with the yarn's linear mass and therefore its diameter. On the basis of Table 2, Fig. 7 represents the average results of the SD in percentage and the sample average in volts for each yarn. There is a strong correlation between the yarn's linear mass, SD, and the average values for the full 360° rotations.

Subsequently, considering as a reference the results of the 360° average from Fig. 7, the type of irregularities detected in each sample of each yarn can be classified. As already mentioned, the samples that have an average value greater than the reference are classified as thick places (neps if the variation is at least 100%) and the ones that have an average value inferior to the reference are classified as thin places. Table 2 presents the statistical analysis performed for samples corresponding to different irregularities, including the sample average, the diameter variation, the SD, the pattern deviation, and the detected faults. It is verified that the pattern deviation value is highly correlated with the distribution of irregularities over the sample. In a homogeneous distribution, the SD values will tend to zero; on the contrary, highly heterogeneous distributions will have large SD values. We note that sample 2 of the 49.2 g/km yarn has an almost homogeneous distribution of diameter variations and a very low level of diameter increase over the average, and sample 6 of the 295 g/km yarn has an extremely heterogeneous distribution of the diameter variations, with an average value somewhat smaller than the overall average diameter obtained for this yarn. Sample 8 of the 62 g/km yarn has an heterogeneous distribution of the diameter variation with a high level of diameter decrease over the average and sample 1 of the 49.2 g/km yarn has an extremely uniform diameter distribution of diameter variation with almost no diameter alteration over the average.

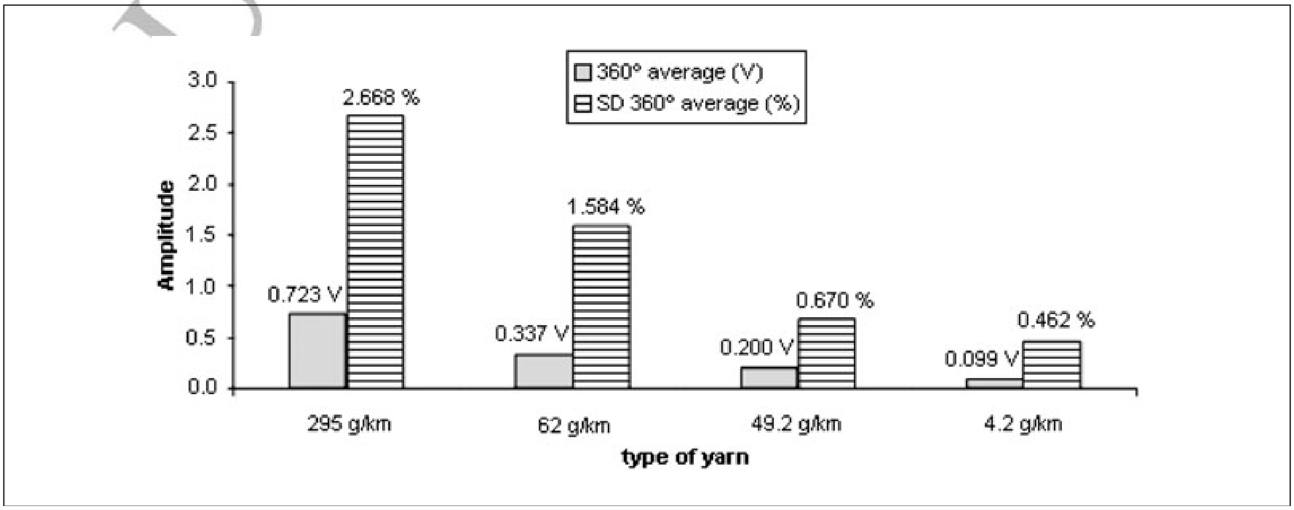

Fig. 7: Average results of SD and average signal for each tested yarn

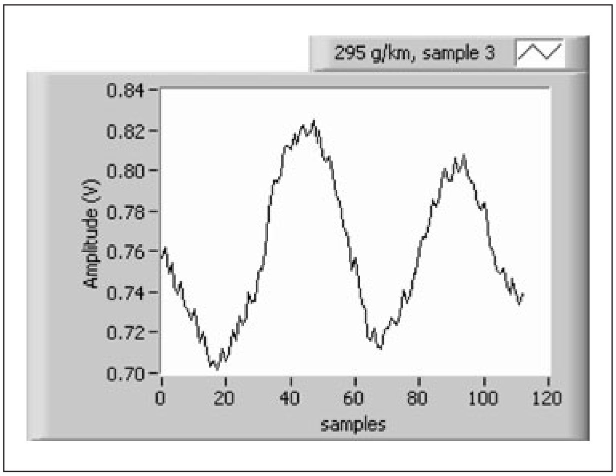

Fig. 8: Signal of a 360° characterization obtained for sample 3 of 295 g/km yarn

As an example, Fig. 8 presents the signal obtained for sample 3 of the 295 g/km yarn, which represents the pattern obtained when a fault is present, confirming that the presented signals are repeated every 180°. The small variations between signals separated by 180° can be related to small yarn oscillations as it was being rotated or more probably because the rotation was performed manually and consequently the rotational speed was not constant.

Afterwards the 360° average results for each yarn (for 10 samples) were correlated with the average SD results obtained for one direction over 6000 samples in groups of 10 samples to establish a more reliable comparison. Figure 9 presents the results. There is a close correlation between the two sets of results. As expected, for the more regular yarns (62, 49.2 and 4.2 g/km), the single projection values agree closely with the values obtained for a 360° analysis.

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Subsequently, we needed to test if irregularities are in fact randomly distributed over the yarn. First of all, we need to know the necessary amount of yarn length (number of samples) required to assure significant statistics. For this purpose, an analysis was made of the yarn possessing the highest level of irregularity (295 g/km). A measurement of this yarn was carried out over 24,000 samples, sampling every millimeter. This resulted in 24,000 total samples for which a running calculation of the average and SD of the signal was kept. Figure 10 presents the evolution of the SD of yarn 295 g/km for 24,000 samples. The results show that 14,000 samples are sufficient to obtain a SD variation limited to the range [−1%; +1%]. The length of yarn required to correctly characterize the yarn irregularities is 14 m. In order to verify if there is any distribution pattern for irregularities, the acquisition signal was compressed in bands, for an easier analysis, over the 24,000 samples of the 295 g/km yarn, as shown in Fig. 11. There does not appear to be any obvious pattern signal present. Instead the irregularity levels appear to be quite randomly distributed. In this case, it is expected that the diameter irregularities will also be randomly distributed over 360° for each yarn sample and given enough samples, the full spectrum of yarn irregularities should be observed. Subsequently, as mentioned above, multiplying the results of a single projection by a factor of 1.57 should give the proper value for the total irregularity of the sample in three dimensions. To confirm these assertions, an analysis of yarn irregularity using two photo detectors oriented along orthogonal directions was performed.

Orthogonal Directions Diameter Characterization

In sample lengths of 5 mm, 19 m of the 62 g/km yarn were analyzed, registering the signal received by each photodiode by two analogue channels of the National Instruments USB-6251 data acquisition board. The signal without yarn for channel 1 was 7.85 V and for channel 2 was 7.46 V.

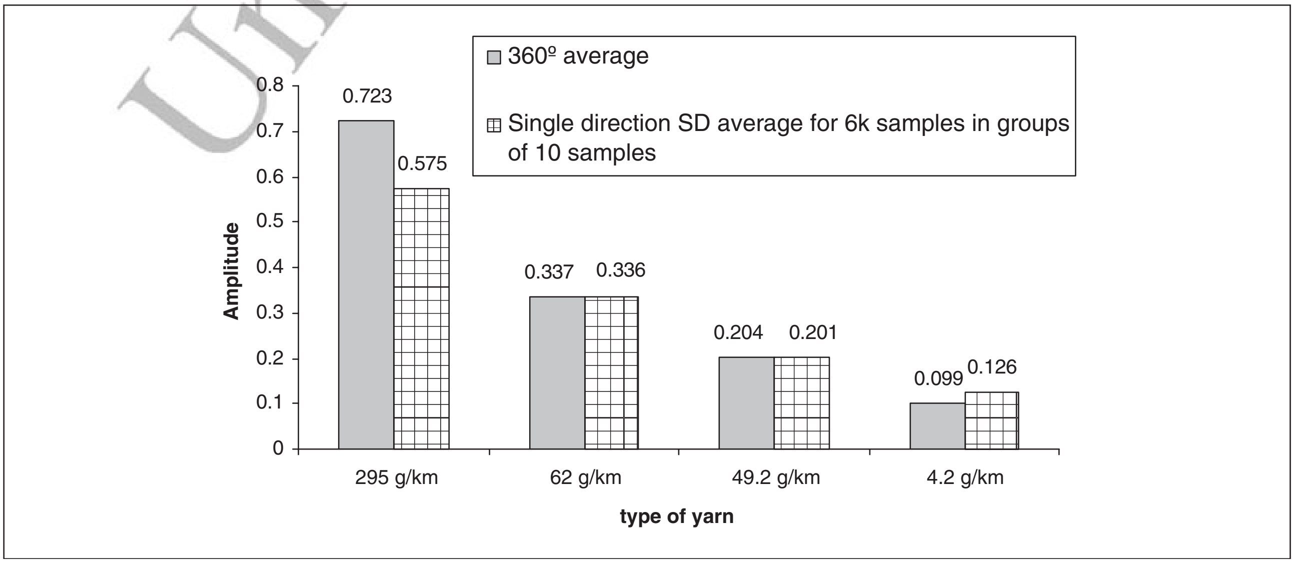

Fig. 9: Correlation between results for one direction and a 360° analysis

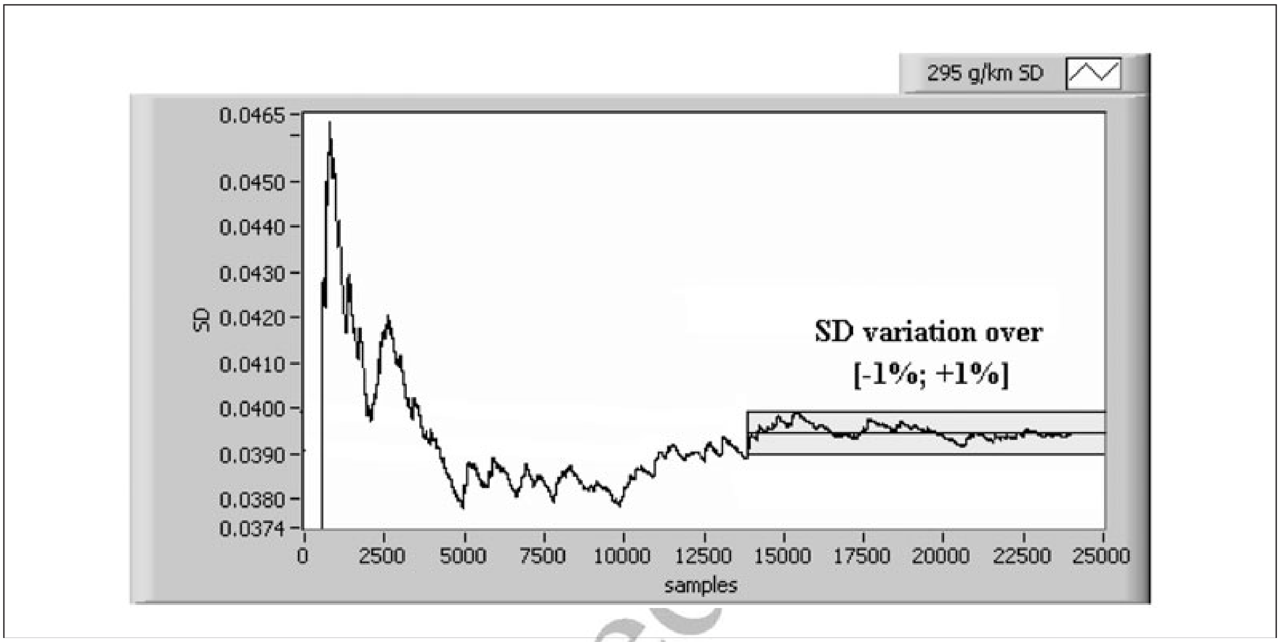

Fig. 10: SD evolution over 24,000 samples

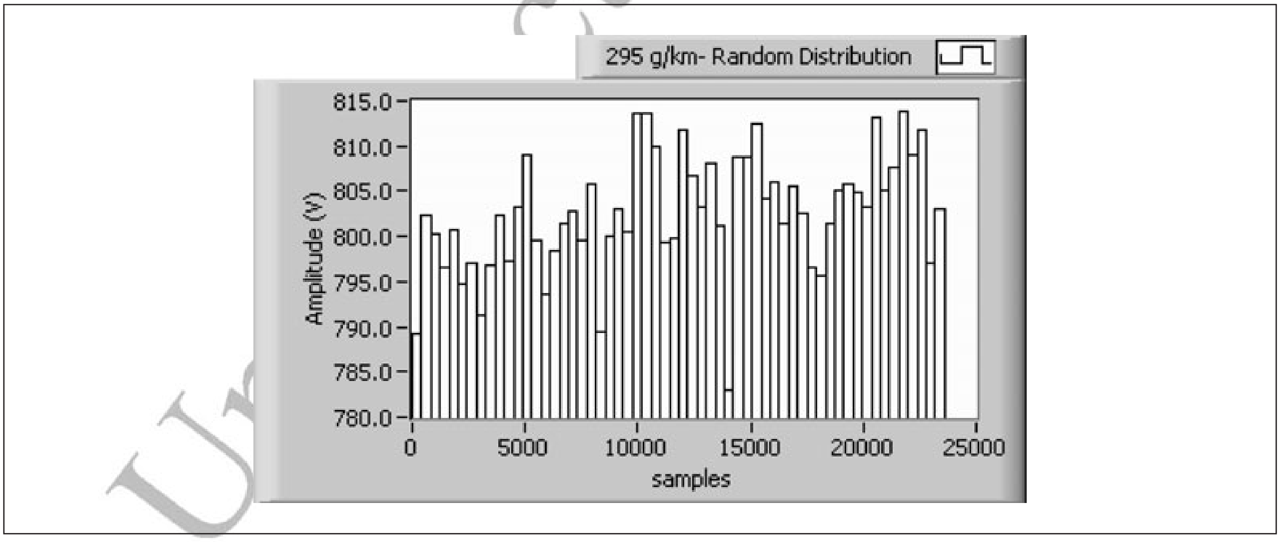

Fig. 11: Compressed acquisition signal for 24,000 samples

Subtracting the signals acquired with the yarn present from the signals without yarn, the signal blocked by yarn for each direction can be determined. Figure 12a and b presents, respectively, the blocked yarn signals obtained for channel 1 and channel 2. An average of 0.450 V and a SD of 6.3% for channel 1 and an average of 0.381 V and a SD of 5.8% for channel 2 were obtained. As expected the average signals are close but not equal. This is because the gains of the transimpedance amplifiers were adjusted to give roughly the same reference level. However, as the laser power was different in each channel, this resulted in different gains for the two channels. Nevertheless, the SD results should be very close as verified. On average, the pattern deviation for the two signals should be close, provided that the irregularities are randomly distributed over the yarn and so will have an equal probability of taking on any orientation over the 360° about the yarn's axis. However, to correctly correlate the signals, their percentage variation over the average must be analyzed. Considering the percentage variation signal obtained for channel 1 and channel 2, a SD deviation result of 14.1 and 15.2% were obtained, respectively. Although these signals look different, they are in fact statistically very similar. To carry out a detailed analysis of the correlation of the signals, their frequency diagrams considering 100 intervals were determined. Figure 13 presents the results obtained, where it can be verified that both signals are

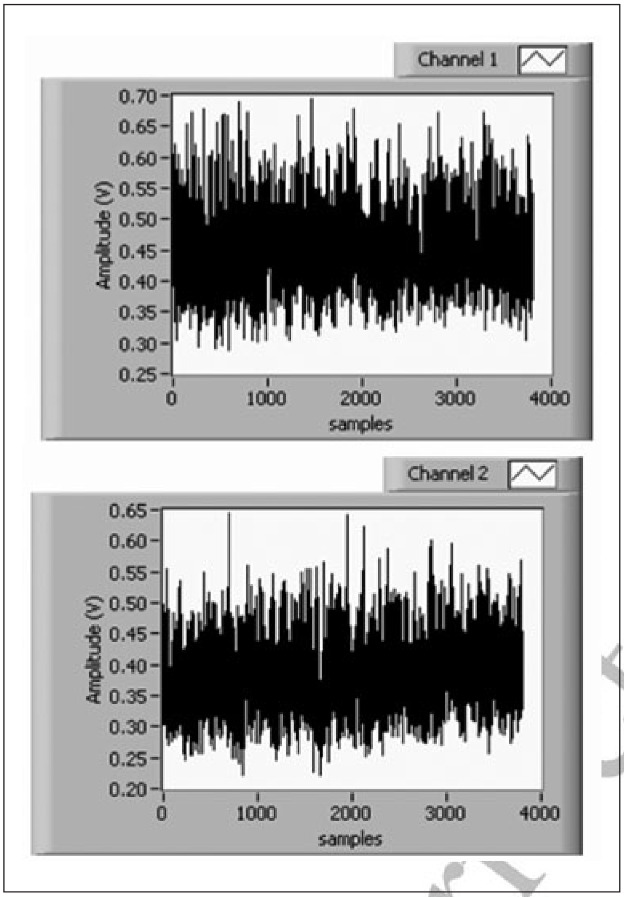

Fig. 12: (a) Blocked yarn signal for channel 1. (b) Blocked yarn signal for channel 2

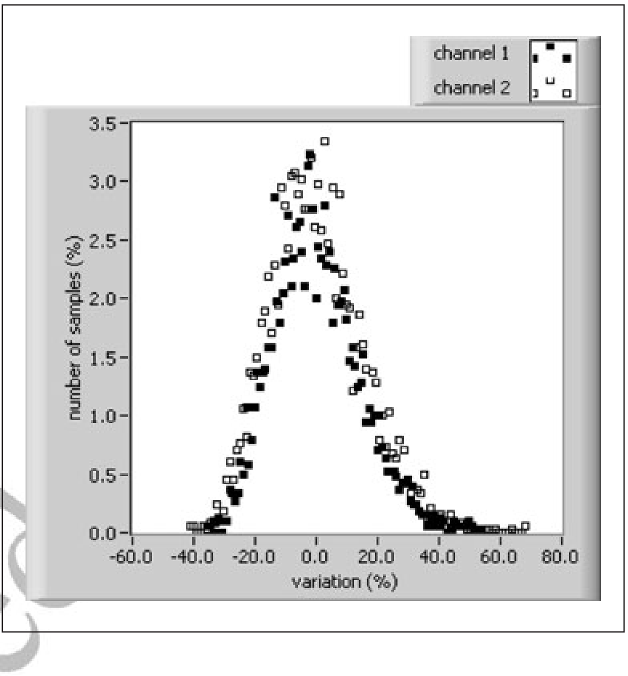

Fig. 13: Frequency diagrams of channels 1 and 2 for the percentage variation signals

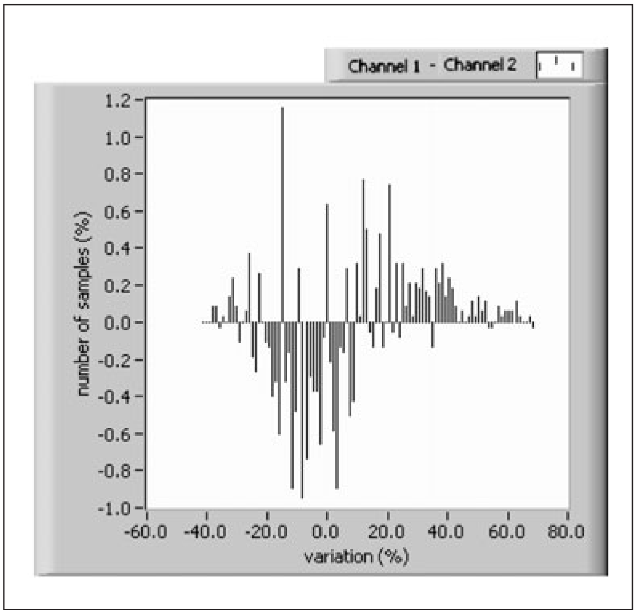

Fig. 14: Amplitude differences in each interval of Fig. 13

highly correlated, regarding the number of samples obtained for each tested interval.

The amplitude differences at each interval are presented in Fig. 14; the amplitude variations over each interval are confined to a small number of samples ranges in the interval [−0.9%; 1.18%]. A SD of 0.33%, a mode of 0.11%, and a mean of 0.22% were obtained. The high level of statistical similarity between the signals supports the claim that the irregularities are indeed randomly orientated. The results obtained support our statement that a single direction measurement can be used to determine the full amount of irregularities of a yarn with an error less than ±2% and a signal deviation of only 0.33%, showing a high reliability. These results can also be used to predict other statistical parameters used for yarn quality control, such as the yarn mass absolute mean deviation (Um) and the yarn mass coefficient of variation (CVm), as they are correlated with the diameter measurements.[20,21]

CONCLUSIONS AND FUTURE WORK

In view of the studies undertaken, it was shown that:

- Considering an output signal directly proportional to yarn diameter, the irregularity pattern over a 360° yarn rotational analysis is repeated every 180° and is well described by an absolute cosine signal modulation.
- The irregularities appear to be randomly distributed over the length of the yarn. This permits one to adequately characterize the yarn's irregularities using a single projection direction provided the number of samples acquired is sufficient to result in a low overall SD (±1%).

- The orthogonal results confirmed that for the number of samples used in the test, a variation between the results of each direction is less than an absolute value of approximately 2% and so are very similar.

The obtained results support our claim that using only a single projection it is possible to quantify, with a high level of confidence given the large number of samples normally used in a test, the total amount of irregularities over the yarn using a factor of 1.57 to account for the single projection results. This factor was confirmed using the results from the overall 360° yarn irregularity analysis, which were well described by an absolute cosine signal irregularity distribution. Moreover, as it is based on a light-yarn signal projection over a photodiode, it is totally independent of the yarn fibers and manufacturing processes. This allows one to use a less complex system at a significantly lower cost with almost the same level of confidence. Furthermore, considering the direct relationship between yarn diameter and linear mass and the system yarn sample length, it is possible, using a statistical analysis based on the percentage variation compared with the yarn average diameter, to determine other types of irregularity (positive variations, thick or nep places; negative variations, thin places; no variation, absent of fault) and also their characteristic lengths. A signal processing study to analyze the pattern error distribution is also possible considering the percentage variation signal.

In the near future, we will concentrate on developing a commercial integrated system using optical and capacitive sensors with the addition of image processing techniques for characterizing simultaneously yarn diameter, hairiness, mass, and production characteristics.

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