Automatic Yarn Characterization System: Design of a Prototype

Vítor H. Carvalho, Michael S. Belsley, Rosa M. Vasconcelos, and Filomena O. Soares

***Abstract*—This paper presents Yarn System Quality (YSQ), an innovative, low-cost, portable and high-precision yarn evaluation tester, for quality control of yarn characteristics under laboratory conditions. It presents a modular architecture, simultaneously integrating measurements of yarn hairiness, mass, regularity and diameter. An external module to obtain the yarn production characteristics using analogue optics and image processing is also available. The quantification of yarn hairiness and diameter variation (with a sampling resolution length of 1 mm) is carried out using photodiodes; the diameter characterization, based on 0.5 mm width samples, employs a linear photodiode array; the measurements of mass variation, based on samples of 1 mm, uses a parallel plate capacitive sensor. In the YSQ measurement parameters based on optical sensors a coherent signal processing technique with Fourier analysis is used, to obtain linear output signal variations. A comparison between the results obtained using the YSQ tester and a commercial solution is also presented.**

***Index Terms*—Capacitive sensors, optical sensors, signal processing, yarn parameterization.**

I. Introduction

THE correct and accurate evaluation of yarns is a subject of major importance to the Textile Industry, as the final fabric quality depends directly on the yarn quality. To undertake these yarn tests several companies have developed specific equipment. Tester 5 from *Uster* [1] and the Multitester from *Zweigle* [2] are important for their relevant contributions to the development of quantitative yarn characterization.

However, both these yarn testers have a significant cost, require a considerable area for their installation, and present limited resolution and precision in the evaluation of certain yarn parameters.

As a result, many yarn producers do not have their own yarn testers and, instead, choose to subcontract dedicated testing laboratories for yarn quality determination. This process is time consuming and eliminates the possibility of acting in useful time during yarn production, reducing efficiency.

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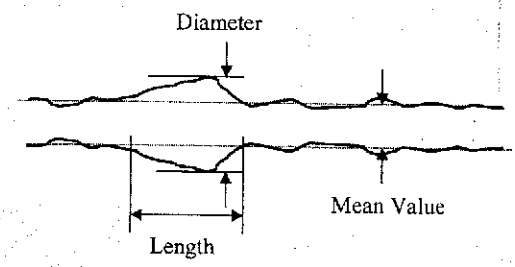

Fig. 1. Yarn configuration example.

To overcome these drawbacks, we have developed a new equipment, entitled Yarn System Quality (YSQ) [3]. The YSQ measures the yarn diameter, the yarn hairiness and the yarn irregularity based on optical and capacitive sensors. Moreover, it integrates an external module to obtain yarn production characteristics, based on image processing. At present, in the Textile Industry there are no available commercial equipment or known prototypes to obtain these characteristics automatically. Instead, they are obtained manually by human ocular inspection or by using an analogue microscope, the results being susceptible to errors [4], [5].

The high precision levels of parameterization performed by the YSQ, together with its low cost and high portability make it a reliable and efficient solution for the Industry.

II. Textile Parameters Theorectical Considerations

This section describes the typical configuration of a yarn, the definition of faults, hairiness and the most important yarn production characteristics [4]–[8].

A. Yarn Configuration, Faults and Hairiness

The most important parameters used to specify yarn quality are linear density, structural features, and fiber content. An example of yarn configuration is shown in Fig. 1.

As Fig. 1 suggests, there is a direct relationship between the variation of yarn mass and the yarn diameter. This fact allows the possibility of determining yarn irregularity based on yarn diameter measurements. The yarn linear mass is generally express in tex which represents the mass of yarn (g) over a kilometer (km).

The number of yarn faults and yarn mass measurements enables a quality rating of the products tested. There are three kinds of yarn faults, classified as (Fig. 2): thin places—a decrease in the mass during a short length (4 mm); thick places—an increase in the mass, usually less than 100% of the sensitivity, and lasting more than 4 mm; neps—huge amount of yarn mass (equal or superior to 100% of sensitivity) in a short length (typically, from 1 to 4 mm). Sensitivity is defined as the

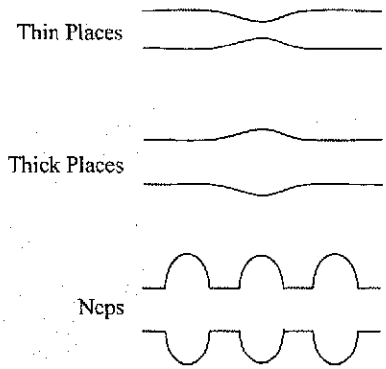

Fig. 2. Types of yarn faults.

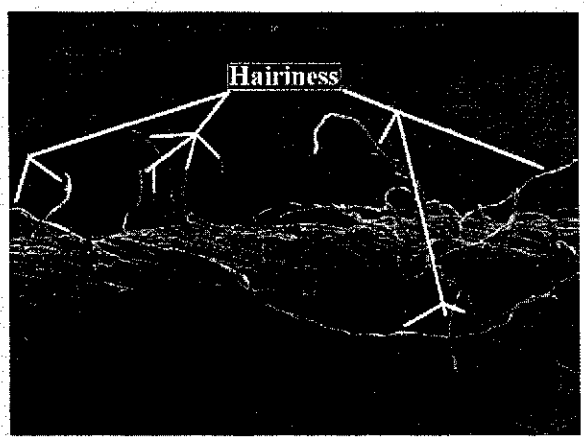

Fig. 3. Identification of yarn hairiness in an electron microscope picture.

yarn mass value used to detect a particular fault, referenced to the yarn mass average. As an example, 40% of sensitivity to classify thick places means that mass measurements above 40% of the mass average are considered a fault; for classification as thin places, the values would be below 40% of the mass average [9].

Apart from faults, another important feature which greatly influences the appearance of fabrics is the level of yarn hairiness. Hairiness is the result of released fibers over the strand. Fig. 3 presents an example of hairiness [4], [7], [10]–[12].

Measurements of the yarn hairiness, mass and diameter, allow the determination of several statistical parameters which are relevant when characterizing yarn quality and, subsequently, the fabrics. Generally, the more common quantified statistical parameters are the U (absolute mean deviation), CV (coefficient of variation), H (hairiness index), and sH (hairiness standard deviation) [8], [13], [14]. The first two parameters (U, CV) and the standard deviation (SD) can be applied to yarn mass, diameter and hairiness measurements. The hairiness coefficient (H), which specifies the length of hairs in a meter of yarn, is only adequate to hairiness measurements.

B. Yarn Production Characteristics

Four important production characteristics of commercial yarns are the fiber's twist orientation, the number of cables [folded yarns (more than one cable) and nonfolded yarns (only one cable)], the folded yarn twist step and the folded yarn twist

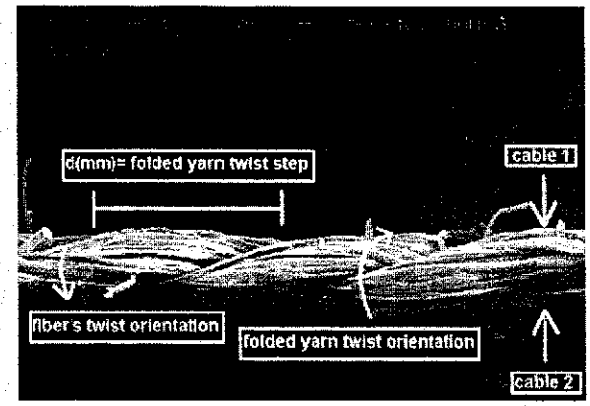

Fig. 4. Identification of the yarn production characteristics in an electron croscope picture.

orientation [4], [5]. The two final production characterist mentioned are only obtained when dealing with folded yar Fig. 4 identifies the four described production characterist using as an example an electron microscope image of a 4.2 g/l cotton yarn. It is a folded yarn as two separate cables are clea visible. The folded yarn twist step (d) is 0.3334 mm, with orientation clockwise and a fiber twist orientation oppos (anticlockwise) to the folded yarn direction.

III. YSQ Sensors System

This section describes the optical and electronic setups u to obtain the measurements of yarn hairiness, yarn diameter, a mass variation in the YSQ [15]–[17]. Moreover, it also descril the hardware of the external YSQ module, employed to obt the yarn production characteristics.

A. Three Directions Optical Configuration—Main Module

In order to reduce the YSQ volume and cost, only one di laser source was employed (Eudyna FLD6A2TK [18]) to est lish three different beams. This single source (Src) was divi in three beams using two beam splitters (S1, first beam spli division 50%/50% of full signal for each resultant direction, second beam splitter division ≈2%/48% of full signal for e resultant direction), as presented in Fig. 5.

Fig. 6 presents the YSQ optical setup employed where, is the diode laser source that emits light at 685 ±10 nm in b a single transverse and a single longitudinal mode, with a l aspect ratio of 1.3, the two HPF represent a high-pass spa filter, LPF is a low-pass spatial filter, FL is the Fourier lens, is the first beam splitter, S2 is the second beam splitter,and to L4 are plano-convex lenses.

Observing Fig. 6 one can see that the beam splitters w placed immediately after the Fourier lens. As in this case, th are two different types of spatial filters [high-pass filters (HP and low-pass filters (LPFs)], the beam division should be p formed before the signal filtering to allow the application of ferent filters. The first beam splitter (S1) makes an equal sig division, whereas the second beam splitter (S2) directs only of the signal to the left arm and transmits 48% to the forw direction (Fig. 5). These choices are taken because the yarn c tours and hairiness require stronger signal intensity, as the jority of the signal component is filtered by the high-pass fi

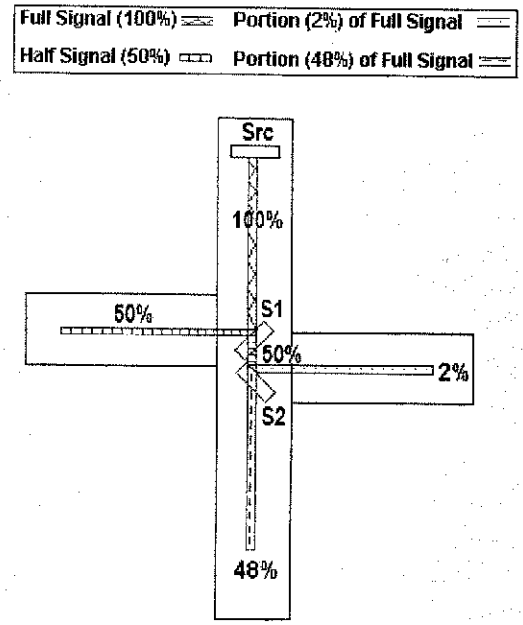

Fig. 5. Light signal source intensity beam division.

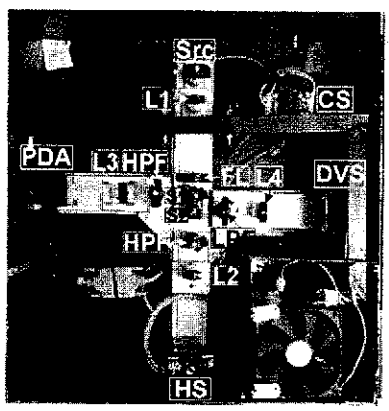

Fig. 6. YSQ optical configuration.

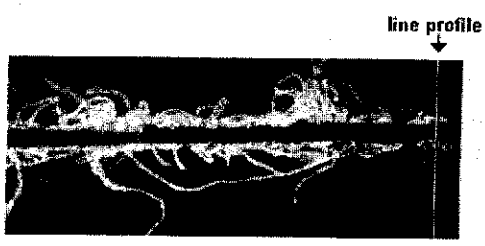

Fig. 7. Image plane of lenses L2 and L3.

[15]. However, the measurements of yarn core diameter does not require high signal intensity, since only the contours and hairiness are filtered by the low-pass filter maintaining the strongest signal components [16]. Fig. 7 presents an image obtained in the image plane of lenses L2 [Hairiness Sensor (HS)] and L3 [Photodiode Array (PDA)], where only the yarn contours and hairiness are highlighted by the high-pass spatial filter (the yarn core and light which is not blocked by the yarn were eliminated).

Fig. 8 presents an image obtained in the image plane of lens L4 [Diameter Variation Sensor (DVS)], where only a shadow

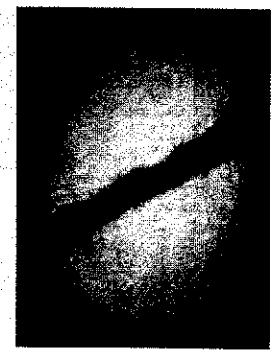

Fig. 8. Image plane of lens L4.

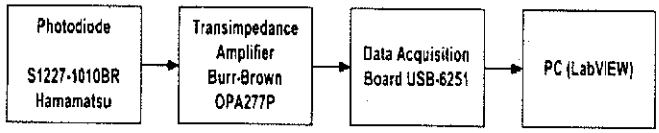

Fig. 9. Custom developed electronic yarn measurement hardware for the HS and DVS.

of the yarn core and light which is not blocked by the yarn are transmitted by a low-pass spatial filter (the yarn contours and hairiness were eliminated).

B. Electronics Configuration—Main Module

The images obtained in the image plane of lenses L2 (HS) and L4 (DVS) are acquired by two equal configurations of the developed electronic yarn measurement hardware shown in Fig. 9 [15], [16].

In Fig. 9, a photodiode (S1227-1010BR) from Hamamatsu [19] was chosen as a receiver. It is a low-cost photodiode, with a high sensitivity for red wavelengths (for the laser used, 0.39 A/W), a large active measurement area (10 mm × 10 mm), a low dark current (maximum of 50 pA), a high shunt resistance (2 GΩ), a noise equivalent power (NEP) of 3.1×10^{-15} W/Hz$^{1/2}$, and a low terminal capacitance (3000 pF). It includes a current to voltage converter (transimpedance amplifier) connected to an analogue channel of the data acquisition board. Software developed in LabVIEW from National Instruments [20] was used to acquire and process the data.

In order to allow a yarn sampling resolution length of 1 mm, an opaque window was placed in front of the photodiodes with a width (mm) equal to the amplification factors obtained in these directions (1.11 and 1.15, respectively, to the HS and the DVS).

The measurement of precise yarn diameter (PDA) was based on line profile analysis [17]. Fig. 10 presents the line profile analysis indicated in Fig. 7 for 512 pixels, where the red plane intensity line profile signal, is proportional to the voltage signal resulting from the hairiness distribution image of the linear array photodiodes.

Considering the typical hairiness distribution profile (Fig. 10), starting from the yarn core signal (reduced signal intensity of between the two main distribution peaks), in the right and left directions, respectively, the first signal peak intensity is obtained for the yarn contours. The algorithm used assures the

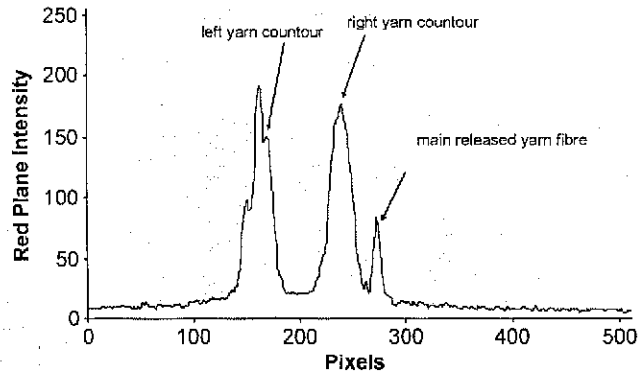

Fig. 10. Line profile analysis example.

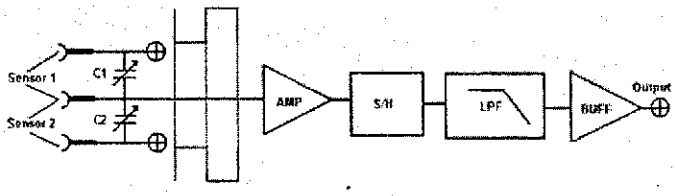

Fig. 11. Capacitive sensor configuration [C1, C2—Adjustable capacitors to calibrate the sensors, AMP—Capacity to voltage converter and amplifier, S/H—Sample and hold, LPF—Two pole low-pass filter, and BUFF—Output buffer].

correct detection of the contour pixels as it first detects the yarn core pixels range with a close to stable intensity and then, with a slope signal analysis, detects the yarn contours pixels—the pixels before the change in signal slope correspond to the yarn contours.

The yarn diameter characterization can be determined considering the number of pixels between the left and right yarn contour pixels, the optical amplification (0.37) and the pixels pitch.

The experimental setup was developed based on the S8378-256Q CMOS line array and the C9001 Driver Circuit, both from Hamamatsu [19]. The main characteristics of the line array are: 256 pixels, pixel pitch of 25 μm, pixel height of 0.5 mm, maximum operating clock frequency of 500 kHz, spectral response range from 200 nm to 1000 nm, relatively sensitivity between 80% and 100% for the used wavelength, sensitivity of 4.4 V/lx.s, on-chip charge amplifier, built-in timing generator, typical dark output voltage of 1.6 mV for low gain (used), typical saturation output voltage of 2.5 V for low gain, typical saturation exposure of 570 mlx.s for low gain, and quartz window material. Taking into account the YSQ PDA used (S8378-256Q), each line profile analysis integrates 256 samples (number of pixels). The data acquisition, control and processing is performed using the data acquisition board and software developed in LabVIEW [20].

The yarn mass variation system considers a 1 mm parallel plate capacitive sensor based on the integrated circuit MS3110 from Irvine Sensors [6], [9], [21], allowing direct yarn mass measurements in samples of 1 mm. The sensor adopts a differential configuration to assure a higher robustness to variations in temperature, air humidity, and pressure. It integrates transducer amplification and signal conditioning, as shown in Fig. 11.

As Fig. 11 shows, the sensor capacitance variation is converted into a voltage signal and amplified. A second-order low-pass filter attenuates the high-frequency interferences that come from an internal oscillator and other external noise sources. The filtered signal is then once more amplified. The signal output is acquired by the data acquisition board and monitored in a PC, using a LabVIEW software application [20]. The capacitive sensor module placement (CS) over the YSQ prototype can be observed in Fig. 6.

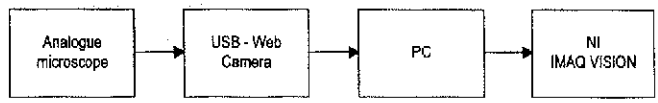

Fig. 12. Yarn image acquisition flowchart.

C. Yarn Productions Characteristics External Module Hardware Design—Optics and Electronics

In order to keep the total system price at an acceptable level, a low-cost analogue microscope coupled to a web CMOS camera was used. The microscope provides sufficient amplification and image detail, while there are no special requirements regarding the camera resolution. Fig. 12 shows the flowchart of the designed system.

The analogue microscope employed is the Biolux Al from Bresser [22], which has the following main characteristics: two oculars of 5× and 16×, three objectives of 4×, 10× and 40×; a Barlow lens of 2×, and led illumination. For all the studies undertaken during the module development, the 5× ocular, the 4× objective and the 2× Barlow lens were used, obtaining an overall optical amplification of 40× (5 × 4 × 2). This amplification level was sufficient to obtain reliable results for yarns within a wide range of linear masses. However, if necessary, alternative magnifications can be used within the limits of the available set of lenses.

The USB Web Camera employed is the Deluxe from Hercules [23], which has the following main characteristics: photosensitive element: 1/4″ CMOS sensor, resolution: 640 × 480 pixels, video mode: VGA, color format: 24 bit—true color. The web camera was placed at the exit plane of the microscope ocular, capturing the analogue image produced by the microscope. With an optical amplification of 40×, it was found that a sensor resolution of 640 × 480 pixels is adequate to correctly evaluate the yarn production characteristics.

In order to obtain higher contrasts for the yarn geometry relief, the illuminated yarn surface must be as close as possible to a monochromatic light source. As the white led illumination available on the microscope emits a wide range of wavelengths, an external yellow light source was used, which is somewhat closer to an ideal monochromatic light source. Fig. 13 presents an example of a picture of a 22 g/km linear mass yarn obtained using the described setup.

Therefore, considering the clear contrast between the yarn zones with higher relief, corresponding to the most accentuated twist areas or yarn areas which are closer to the light source (as seen in Fig. 13), a tool was developed using the IMAQ Vision software [24]–[26] for LabVIEW, to determine the yarn production characteristics. This tool considers the following IMAQ Vision image processing functions, sequentially: contrast adjustments, gamma adjustments, removal of the luminance place

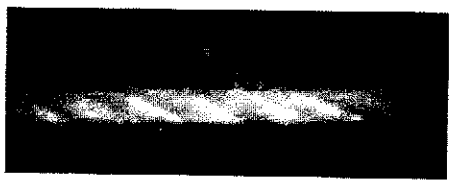

Fig. 13. Picture of a 22 g/km yarn.

over the hue saturation luminance color space, threshold, hole filling, erosion, convex hull, small objects removal, and particle analysis (first horizontal pixel, determination of orientation and area) [24]–[26]. Then, considering the parameters obtained with the particle analysis function, it was possible to classify the yarn production characteristics.

- Folded (multiple cable) yarn twist step: obtained by the average of the horizontal pixel distance between particles.
- Folded yarn twist orientation: determined by the orientation angle for each particle, under the following conditions: If the orientation angle lies between 90° and 180°, then the twist orientation is anticlockwise; If the orientation angle lies between 0° and 90°, than the twist orientation is in the clockwise direction.
- Number of cables (folded or nonfolded (single) yarn): If only one particle is identified—single cable (nonfolded yarn); If the number of particles is greater than one—multiple cables (folded yarn).
- Fibers twist orientation: In folded yarns, the fibers twist orientation is opposite to the twist orientation. This is a general fact in the Textile Industry to avoid the fibers untwist over the yarns [4], [5].

Finally, although all developed software modules were integrated, the hardware of the yarn production characteristics module has not been integrated in the YSQ main module hardware (Fig. 6).

IV. Yarn Parameterization Comparison Between Uster Tester 3 and YSQ

This section presents a comparison between statistical and signal processing results obtained with the YSQ prototype (Fig. 6) and the commercial solution Uster Tester 3 [1], for two yarn samples: a 59 g/km linear mass and a 22 g/km linear mass 100% cotton yarns.

A. Statistical Results Comparison

Due to the eight times superior resolution of the YSQ capacitive mass measurements (yarn samples of 1 mm length), it is verified that, as expected, the measurements of U, CV and irregularities, present significantly higher variations in comparison to the Uster Tester 3 [see columns (a) and (b) of Table I and their respective variations in Table II]. Furthermore, since the YSQ does not consider the yarn contours as hairiness, as they are a characteristic of the yarn and are not hairiness, (in contrast to the operation of the Uster Tester 3), the YSQ presents a much lower hairiness coefficient than the Uster Tester 3. The difference obtained is justified as the signal due to yarn contours is highly significant in the hairiness measurement in the Uster Tester 3 measurements. Finally, as this signal (yarn contours) could be considered approximately constant for a specific yarn, the variations detected over it (hairs) remain similar, justifying the relative similarity obtained in the standard deviation of the hairiness coefficient (sH), on both instruments.

TABLE I
Statistical Parameters Results

Parameter	Uster Tester 3 (a) (capacitive and optical sensor)	YSQ (b) (capacitive and optical sensor)	YSQ (c) (photodiode array sensor)
U (%)	11.40	15.68	16.43
CV (%)	14.50	20.20	22.91
Thin Places (-50 %)	2/km	1345/km	62352/km
Thick Places (50 %)	54/km	7365/km	8235/km
Neps (>= 200 %)	17/km	255/km	3529/km
H	8.20	1.45	1.52
sH	2.30	2.47	2.61

TABLE II
Statistical Parameters Results Absolute Variation

Parameter	Absolute variation (b - a)	Absolute variation (b - c)	Absolute variation (c - a)
U (%)	+ 4.28	- 0.75	+ 5.03
CV (%)	+ 5.70	- 2.71	+ 8.41
Thin Places (-50 %) / km	+ 1343	- 61007	+62350
Thick Places (+50 %) / km	+ 7311	- 870	+ 8181
Neps (>=+200 %) / km	+ 238	- 3274	+ 3512
H	- 6.75	- 0.07	- 6.68
sH	+ 0.17	- 0.14	+ 0.31

In addition, Table II also presents a comparison between the YSQ data obtained using capacitive and optical sensors [column (b) of Table I] and the YSQ data obtained using a photodiode array [column (c) of Table I]. Observing these two YSQ data columns in Table I and their respective variations in Table II, it is demonstrated that almost all tested parameters show nearly identical results, especially in absolute terms, as expected for the yarn hairiness parameters (H and sH), as a result of the similar measurement technology (optics based). Furthermore, even the results of U and CV, considering different technologies of measurement (capacitive/optical based) and different segments of the same yarn are highly similar, reflecting the strong relationship between yarn mass and diameter. However, the results of irregularities present a significant variation. This is due to the superior resolution that characterizes the photodiode array and from the influence of yarn hairiness and contours in the capacitive sensor, increasing considerably in some cases the yarn mass value, which is not verified in the diameter measurements. Although, as observed, the dispersion indicators remain approximately similar, enabling a reliable yarn characterization using the photodiode array.

Finally, a comparison between the photodiode array results and the Uster Tester 3 was also performed in Table II. In this case, as the results of the dispersion levels U, CV, H, and SH between Table I columns (b) and (c) closely match the relationship between columns (c) (photodiode array data) and (a) (Uster Tester 3) is relatively close to the one obtained between columns (b) and (a). However, in the absolute irregularities detection, the

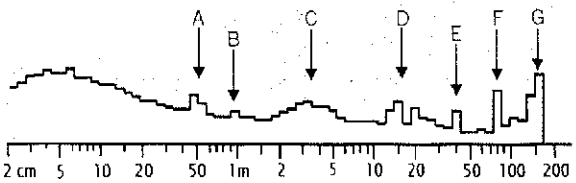

Fig. 14. Uster Tester 3 mass spectrogram.

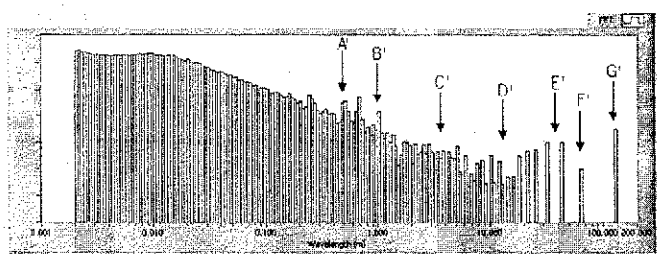

Fig. 15. YSQ mass spectrogram.

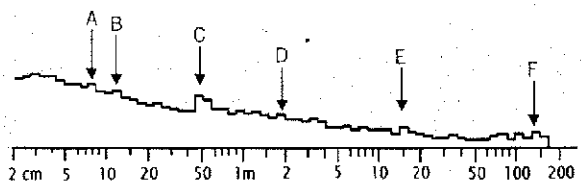

Fig. 16. Uster Tester 3 hairiness spectrogram.

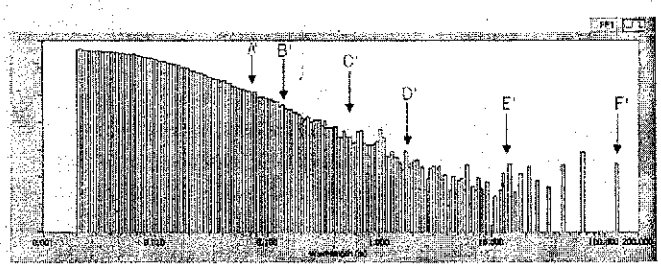

Fig. 17. YSQ hairiness spectrogram.

difference between columns (b) and (c) is even more significant than the obtained between columns (b) and (a). Concerning the resolutions, methodologies and technologies approaches used, these results can be justified by the reasons presented in the previous paragraphs, namely: the use of different technologies (capacitive versus optical), the superior resolution of the photodiode array and the influence of hairiness in the capacitive sensor, which remain valid for this case.

B. Signal Processing Results Comparison

Figs. 14 and 15 present, respectively, the mass spectrogram obtained with the Uster Tester 3 and with the YSQ. While, Figs. 16 and 17 present, respectively, the hairiness spectrogram obtained with the Uster Tester 3 and with the YSQ.

Comparing Figs. 14–17, it is observed that the signals are very similar (mathematically) considering the same wavelength ranges (2 cm to 200 m). In particular, all protruding wavelengths identified by the spectrograms of Uster Tester 3 (A to G in the mass spectrogram of Fig. 14 and A to F in the hairiness spectrogram of Fig. 16), were also identified by the spectrograms of the YSQ (A′ to G′ in the mass spectrogram of Fig. 15 and A′ to F′ in the hairiness spectrogram of Fig. 17). However, due to the higher acquisition frequency used in the YSQ (1 mm samples), it is possible to detect wavelengths in the [2 mm, 2 cm] range, which are impossible with the longer samples measured by the Uster Tester 3. As cotton fiber lengths are in this range, this feature allows a more detailed quality analysis [14].

Fig. 18. Resulting image of the 22 g/km yarn after the image processing techniques employed.

C. Yarn Production Characteristics Results

As there are no available commercial equipment to determine yarn production characteristics, YSQ performance could not be compared. Although, as an example of results, using the methodology described in Section III-C, the final processed image obtained for the yarn of Fig. 13 is presented. The following production characteristics were obtained (Fig. 18): fiber twist orientation: clockwise, folded yarn twist orientation: anticlockwise, number of cables: more than one cable (folded yarn) and folded yarn twist step: 0.40 mm.

V. Conclusion and Future Work

In comparison with the available commercial systems, the YSQ presents several new characteristics, namely: the simultaneously use of the coherent optical signal processing for yarn hairiness and diameter characterization; autocalibration procedures of yarn hairiness reference [27] and diameter determination [16]; integration and measurement of yarn mass variation based on 1 mm capacitive sensor enabling the direct detection of nep irregularities [9]; determination of new parameters in yarn analysis allowing a high precise yarn characterization; use of three signal processing techniques, enabling an accurate periodical errors characterization; automatic determination of yarn production characteristics; modular integration of yarn mass measurement, hairiness measurement, diameter variation measurement and precise diameter determination; reduced dimension, enabling a high portability; application in laboratorial analysis or in Industry for yarn quality control. In summary, the YSQ apparatus is a low-cost system, characterized by superior yarn parameterization, high resolution, and precision. This permits a lower waste, resulting from the reduction of the yarn sample length analysis and allows a quality control for the desired producer level of yarn sensitivity.

The YSQ characteristics will increase the quality of the yarn produced, resulting in a superior production efficiency, as a more detailed yarn quantification will be performed. In addition to these technical advantages, there is also an economic advantage, as the cost employed to undertake highly detailed yarn evaluation is much reduced in comparison with present commercial systems.

Further work will be aimed towards obtaining several improvements: the development of custom made photodiodes with

only the necessary active area for yarn hairiness determination and yarn diameter variation determination, reducing the background noise generated by the use of photodiodes with partial active areas blocked; the study of the hairiness spatial yarn position based on yarn hairiness measurements using a line array; the integration of the external yarn production characteristics module into the main module; the design and addition of a yarn sample closed-loop system for eliminating the yarn waste in tests and allow multiple examinations of the same portions of yarn sample; evolution of the YSQ to a more compact and lighter commercial prototype including, as an example, a user touch screen interface and a report printer and, the possibility of measuring precisely yarn diameter and hairiness using a single line array-based system with fast custom developed hardware and software to reduce the computational effort and increase the efficiency.

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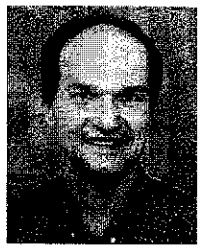

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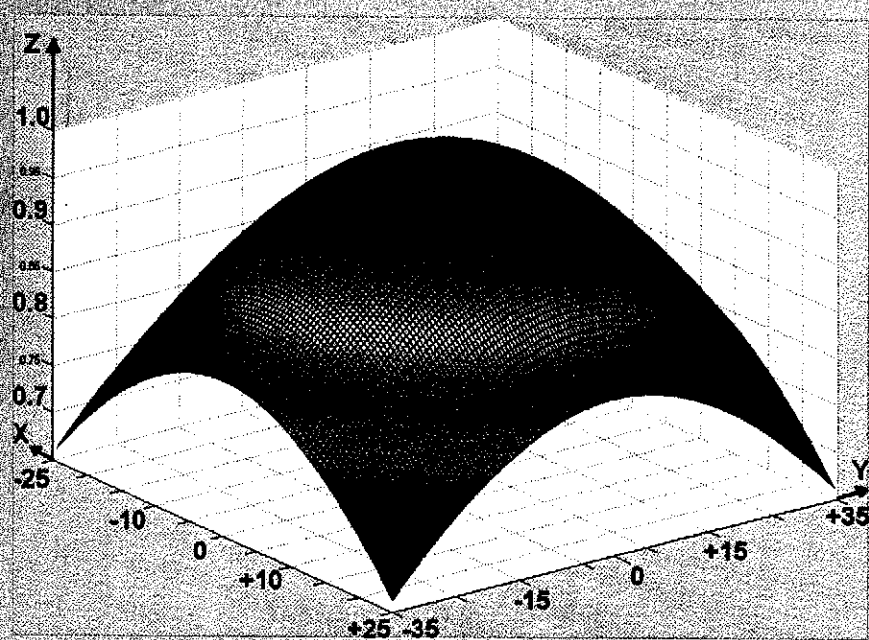

Gaussian amplitude distribution of the localized-mass sensor's responsivity (see page 899).