

A comparative study between yarn diameter and yarn mass variation measurement systems using capacitive and optical sensors

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This paper reports a comparative study between yarn mass and yarn diameter measurement systems using a differential capacitance tester and an optical coherent signal processing diameter tester respectively. A full description of the systems is presented along with their new contributions, namely 1mm length samples analysis for a capacitive tester and optical signal processing to eliminate the influence of hairiness while measuring the diameter. It is proven statistically that the yarn mass measurement systems based on capacitive testers give similar results to that of optical diameter measurement system when identical yarn samples are used. A detailed test report of a cotton yarn with a linear mass of 295 g/km is presented.

Keywords: Capacitive sensors, Optical sensors, Optical signal processing, Yarn diameter, Yarn mass

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1 Introduction

One of the parameters used to assess yarn quality is the irregularity value. The optimal value is obtained with an equal number of fibres in each cross-section (longitudinal variation). Irregularity is also used to evaluate variation in several characteristics along a strand (yarns, roving, sliver or tops), and unevenness measures the mean variation in linear density of a strand or part of it in fibre arrangement. This influences the appearance of the final woven product, and in view of yarn processing efficiency there are levels of unevenness beyond which the yarn is unacceptable.¹

Nowadays, electronic capacitance testers are still applied as a convenient and reliable method of testing irregularity (determination of linear mass). The most commonly used industrial systems, such as ZT5 (Zweigle²) and Tester 5 (Uster³), use capacitors with 8 mm length, allowing measurements with 8 mm resolution. However, as most of the irregularities have a short length (1-4 mm), an assessment evaluated in 1mm range is of utmost importance for a correct and direct characterization.⁴

Optical sensors are also used to test irregularity with a working principle based on the diameter measurement variation, and not on mass variation. This could also be considered an appropriate irregularity determination method as mass variations imply diameter variations.⁵⁻⁸ The most commonly used commercial system based on this methodology is the Oasys from Zweigle⁹, but it considers a sample measurement field of 2mm. Also, in this system yarn hairiness can have a significant and undesired influence by reducing the signal received by the optical sensor, consequently leading to diameter measurement with an error by excess.

The present work is aimed at carrying out tests with 1 mm samples using capacitive and optical sensors to compare their results. Moreover, in the diameter measurement system, a coherent signal processing technique based on Fourier optics¹⁰⁻¹² was used to eliminate the influence of yarn hairiness, thereby increasing the results accuracy.

2 Materials and Methods

2.1 Theoretical Considerations

Capacitive Sensors

Parallel plate capacitive sensors are traditionally formed by two electrodes of section S , separated by a

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distance d . The capacitance obtained depends on the plates section, their distance and the dielectric susceptibility of the material between the plates.¹³ This specific research work aims at establishing a relationship between the capacity and the yarn mass, as the dielectric susceptibility between the plates (yarn) will vary, depending on the yarn composition and diameter.⁴ The capacitance of a parallel plate capacitor is determined using the following equation:

$$C = \frac{\epsilon_0 \epsilon_r S}{d} \quad \dots (1)$$

where C is the capacity (F); $\epsilon_0 = 8.854 \times 10^{-12}$ (F/m); ϵ_r , the dielectric relative constant (1 for vacuum); S , the plates area (m^2); and d , the distance between the plates (m). Equation (1) shows that if the dielectric constant (ϵ_r) is changed, the capacity also changes; phenomenon that occurs when the yarn is inserted between the plates. A relationship can then be established between the capacity and the yarn mass.

However, the use of capacitive sensors has some drawbacks. They are very sensitive to humidity levels, causing some troubles as the dielectric constant of humid air is inferior to the dry air. This situation happens frequently and results in a varying voltage level of the sensor in the absence of yarn between the plates, depending on the local humidity. Therefore, it is generally recommended to carry out the tests in a controlled environment.

To overcome this problem, an integrated amplification circuits that auto corrects the capacitive sensors is used. Furthermore, the software developed solves this problem using the value acquired without yarn as a calibration value. This task can be performed at the start of each test and assumed to be valid during the entire test duration, as the humidity changes typically occur over a relatively long period.⁴

Optical Sensors

Optical sensors are used to perform yarn analysis based on an absolute measurement principle [algebraic difference between the quantity of light received without yarn (reference) and that received with yarn for each analysed sample] (Fig. 1). Traditionally, these sensors have infrared wavelengths which vary between $1\mu m$ and $1mm$ (refs 7, 14).

Often a coherent light source (laser or laser-diode) due to the higher spatial homogeneity of the light distribution.^{15,16} For the sensor, a single photodiode is sufficient to determine the level of

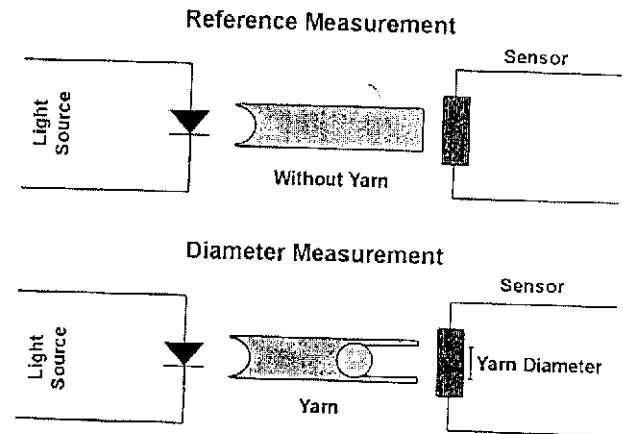


Fig. 1—Diameter measurement principle

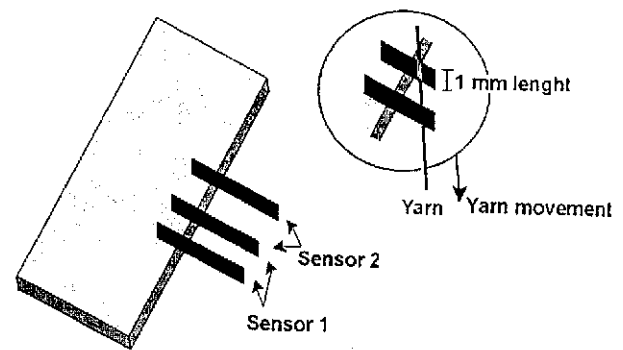


Fig. 2—Yarn mass measurement based on a differential configuration between two parallel plate capacitive sensors

variations ($\pm 30\%$), traditionally considered as irregularities.^{7,17} However, if high precision is requested, the use of a photodiode line-array is more appropriate. In both cases, additional electronic hardware, namely a trans-impedance amplifier (I-V converter), is needed.¹⁸

2.2 Proposed Experiment

2.2.1 Design of Capacitive Sensor for Characterization of Yarn Mass Variation

A new capacitive sensor with parallel plates was developed together with the electronic conditioning circuit, allowing reliable 1–4 mm yarn mass measurements. The studies undertaken show that a capacitance variation of $2.08E-17$ F is expected when a 57 tex (g/km) yarn is used.⁴ Nevertheless, careful design of conditioning circuits was needed due to the low Signal-to-Noise Ratio (SNR).

As radiation is a major problem, a differential configuration using two sensors was employed (Fig. 2). With this technique, it is also possible to use the same equipment for different yarn diameters,

although not simultaneously. The use of a differential set-up makes the electronic circuit more robust to temperature and air humidity variations, which are particularly important in textile industries.

This system is to be used for on-line control of a ring spinning frame to evaluate the produced yarn evenness. At present, this assessment is made off-line in a laboratory using a small amount of yarn. The tests carried out with this system show good performance in a laboratory environment. The experimental set-up used consists of a personal computer (PC) with a data acquisition system together with a 1 mm sensor and electronics. Figure 3 shows the schematic diagram of the system used in the project development.

In order to have two capacitors with a common electrode, three metallic conductors placed in parallel were used in the system design. The integrated circuit, (IC) MS3110) (ref. 19) from *Irvine Sensors*, performs functions related to transducer amplification and signal conditioning. Its use is specific for capacitive sensors and has the following characteristics:

- Capacitance resolution up to 4.0 aF/rHz,
- Single or dual differential variable,
- On-chip dummy capacitor for quasi-differential operation and initial adjustment,
- Gain and DC offset trim,
- Programmable bandwidth adjustment 0.5-8 kHz,
- 2.25 V DC output for ADC reference/ ratiometric operation,
- Single supply, and
- On-chip EEPROM for storage of settings.

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 the internal oscillator and other external noise sources. The filtered signal is then amplified (Fig. 4).

The signal output is converted into a digital signal using an analogue-to-digital converter (ADC) included in the data acquisition (DAQ) board (USB-6251 from National Instruments²⁰), which is monitored with a PC using LabVIEW²⁰ developed control software. This software allows the data storage, manipulation and processing.

2.2.2 Design of Optical System to Quantify Variations in Yarn Diameter

The yarn diameter measurement system (Fig. 5) is an adaptation of a previously developed measurement system using coherent optical signal processing for

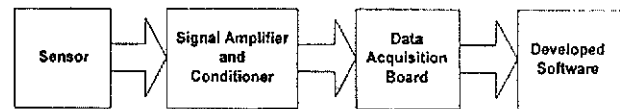


Fig. 3—Yarn mass measurement system flow chart

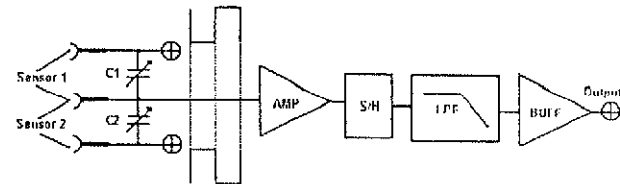


Fig. 4—Sensor plates and MS3110 block diagram [C1,C2—Adjustable capacitors to calibrate the sensors, AMP—Capacity to voltage converter and amplifier, S/H—Sample and hold, LPF—Two pole low pass filter, and BUFF—Output buffer]

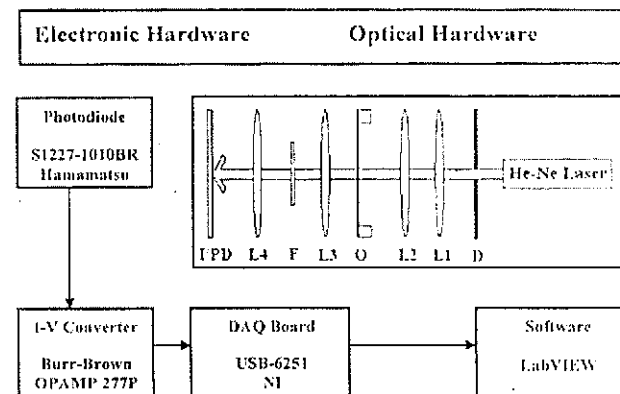


Fig. 5—Electronic and optical hardware used in diameter measurement system

yarn hairiness determination.^{7, 21-25}

The objective of the optical set-up is to obtain a signal proportional to the yarn diameter in the final image plane (I) [position of the photodiode (PD) in Fig. 5]. Coherent light from a helium-neon (He-Ne) laser is incident on a variable diaphragm (D) to ensure a good transverse spatial profile. After the diaphragm, the laser beam passes through a two lens beam expander telescope (L1 and L2) and is directed to the yarn, placed in the object holder (O). The size of the object image is controlled by the lenses L3 and L4.

A custom fabricated spatial filter (F) is placed in the Fourier plane of L3 to process the image, enabling only the low spatial frequencies in the image to propagate further (low pass spatial Fourier filter). This is opposite to the yarn hairiness measurement system which includes a high pass spatial Fourier filter. The low-pass spatial filter produces an image consisting in the yarn core shadow, represented in

black, as well as the incident laser light which is not blocked by the yarn. However, elements with high spatial frequency content, such as small hairs released from the yarn core, are eliminated by the low-pass spatial filter.²¹⁻²⁵

The objective of the electronic hardware is to obtain a voltage signal related to the yarn diameter. The output of a trans-impedance amplifier¹⁸ connected to the photodiode is read by the DAQ board. However, as the intensity of the laser light that is not blocked by the yarn is sufficient to cause the photodiode saturation, a linear polarizer is placed before the photodiode, which has been adjusted to attenuate the laser light signal. In order to obtain a better SNR when the yarn is placed, the polarizer should be adjusted to produce a large signal within the linear response region of the photodiode. Moreover, to increase the SNR, the photodiode region which is not blocked by the yarn can also be reduced.

An image of a yarn resulting from the optical hardware, without the application of any kind of spatial filter, is shown in Fig. 6a. It is observed that the laser light, which is blocked by the yarn (yarn core, contours and hairiness), produces black shadows in the image plane. So, considering the image without yarn as a reference (no blocked regions), and subtracting the image with yarn (with blocked regions), an image resulting from the yarn is obtained, which depends on its diameter. Then, using the previously developed electronic hardware (essentially a photodiode and a trans-impedance amplifier), this light signal is converted into a proportional voltage. However, by analysing carefully Fig. 6a, it is observed that the yarn hairiness which is already measured by the previously developed system can block a significant part of the laser beam signal.²¹⁻²⁵ For a yarn diameter measurement system, these hairiness shadows are considered an undesired signal. To eliminate them, a low-pass spatial optical filter is used in the Fourier plane with the same cut-off frequency of the high-pass spatial filter considered in the hairiness system to obtain the signal components only from the yarn core and laser light which is not blocked by the yarn core.

Figure 6b shows an image resulting from the application of the low-pass spatial filter in which the hairiness is eliminated and only the shadow from the yarn core is visible.

As diameter variations imply a linear yarn mass change per unit length, this approach is suitable to quantify most common irregularity yarn parameters¹,

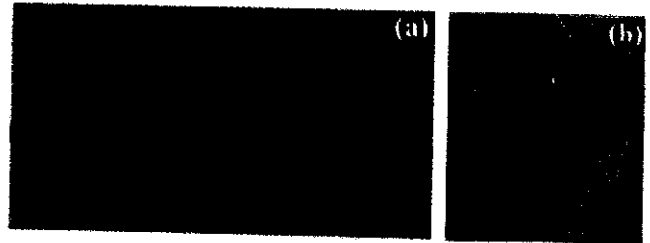


Fig. 6—Examples of yarn images, without optical signal processing (a) and with the application of a low-pass spatial filter (b)

such as the mean absolute deviation (U) and the coefficient of variation (CV). So, considering the high number of samples which are taken in a simple test, the average results for mass and diameter variations should be similar. This indicates that the irregularities have a random spatial orientation, and hence show equal probability of being aligned along any direction within the 360° perpendicular to the yarn core. On an average, the single projection acquired with the optical set-up shows 64% of the total irregularities present which is in agreement with the earlier findings.^{26, 27}

3 Results and Discussion

To observe if there is a high correlation between yarn mass variation and yarn diameter variation, the variation relative to the mean value of a 295 g/km cotton yarn is measured, using the previous described techniques for samples of 1 mm. As the optical sensor (image plane) receives a light signal with approximately 50 % reduction, it means that 1 mm in the image plane corresponds in the object plane to approximately $1/0.5 = 2$ mm, with an error inferior to 15 %. Hence, for a direct comparison between measurements, the capacitive sensor samples need to be grouped in pairs (2 mm) (average of two samples of 1 mm). Although, the measurements are not performed simultaneously, two different samples of the same yarn are used and so the measurement level of variation should be similar.

Figures 7a & 7b show respectively the optical and capacitive sensor variations relative to the mean signal value. On comparing the signals in both the figures, it is verified that a 'cleaner' signal is obtained for the optical sensor, as the capacitive sensor is more susceptible to humidity, temperature, pressure variations, and electromagnetic radiation. However, as reported earlier, these problems have already been reduced using a differential configuration over the capacitive sensor and shielding the electronics with an

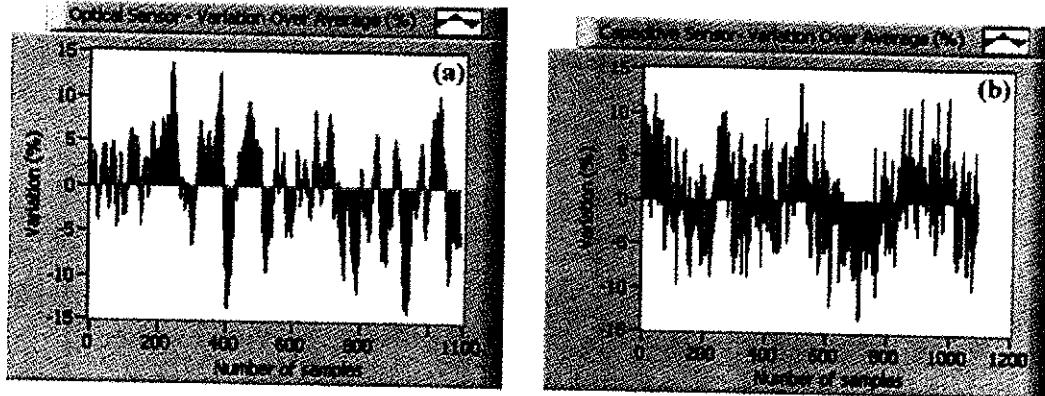


Fig. 7—(a) Optical sensor output voltage signal variation relative to the average, and (b) capacitive sensor output voltage signal variation relative to the average

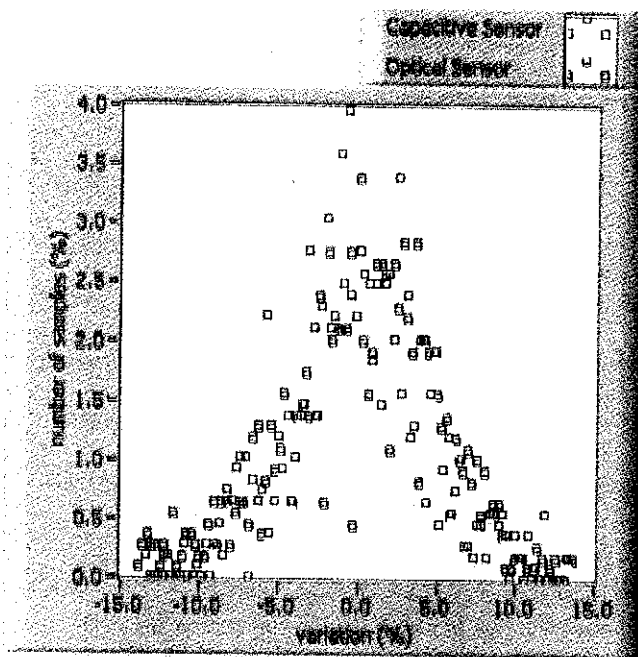


Fig. 8—Frequency diagrams of the capacitive and optical sensors results

acrylic box. So, a reliable comparison between signals can be performed. It is observed that for both signals, the range of variation is very similar and contained in the interval $[-15\%; 15\%]$ and that the standard deviation (SD) results are 5.04 % for the optical sensor signal and 4.36 % for the capacitive sensor signal.

Subsequently, for a detailed analysis of the correlation between these signals, their frequency diagrams are analysed, considering 100 intervals (Fig. 8). It is observed that both the signals have a good correlation, regarding the number of samples obtained

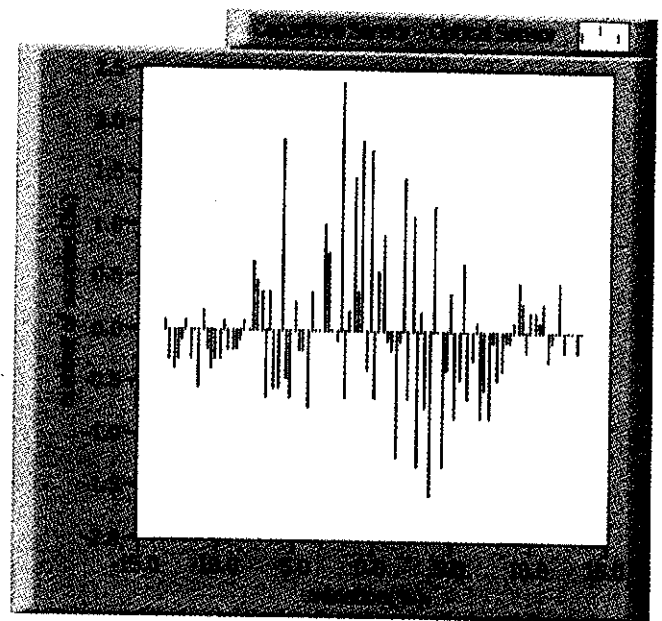


Fig. 9—Amplitude difference for each frequency diagram interval

for each tested interval. The amplitude differences at each interval are shown in Fig. 9. The figure shows low amplitude variations, which are admissible since the range of the number of samples is between -1.5% and 2.4% . The analysis was performed with two different samples of the same yarn and using two different technologies with distinct sensitivities to external influences. Moreover, a SD of 0.67 %, a mode of 0.41% and an absolute mean of 0.46% were obtained in the amplitude differences. The low level of SD confirms that high amplitude differences variations have a low occurrence, as a result of the signals proximity.

Table I—Statistical comparison between optical and capacitive results

Method	Amplitude range %	Minimum variation %	Maximum variation %	Mean variation %	Mean SD error	Inter-quartile range %	Covariance %
Optical	27.81	-14.00	13.81	0.17	0.15	6.58	25.37
Capacitive	26.82	-13.47	13.35	0.03	0.13	5.33	19.02

The statistical similarity between the capacitive and optical sensors results was also supported by the descriptive analysis and correlations performed with SPSS tool²⁸ as presented in Table I. It is found that the determined parameters are in close agreement. Moreover, the correlation is significant at a 0.05 % level. So, as expected these results emphasise the statistical similarity between both technologies.

4 Conclusions

Based on the similarity of the results obtained as characterizes by the SD, amplitude range variation, frequency diagrams and the results using the SPSS tool, it is inferred that there is a significant relationship between mass and diameter variation. This validates the parameterization of yarn irregularities based on diameter measurement. However, the results of the two techniques could not be considered equal or absolutely equivalent, as an absolute mass measurement requires always a capacitive measurement due to the different yarn geometries and material density used. But, it is found that with diameter measurement it is possible to determine the irregularity intervals of a given yarn. Moreover, by adjusting the optical imaging system, yarn sections with a length inferior to 1 mm could easily be sampled, enabling measurements with a higher resolution.

Industrial Importance: The study is useful as it shows simultaneous measurement of yarn irregularity and yarn diameter using only one optical sensor without the undesired influence of hairiness and up to very high resolutions.

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