Process Control for Total Quality in Circular Knitting

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Abstract

This paper deals with a problem of major concern to the knitting industry, which is fabric defects. When a defect occurs, the knitting machine has to be stopped and the fault corrected, thus resulting in time loss which is uneconomic. Eventually, the knitted fabric may be rejected if quality requirements are not met. An effective monitoring of the knitting process is required in order to avoid or detect and locate a defect and its cause as soon as possible, avoiding productivity and quality losses.

In circular knitting machines the yarn input tension (T_i) can be used as a means of process control, so that defects may be prevented or quickly detected. This was found to be a valuable approach to accomplish this task, since it reflects the general behaviour of the knitting machine. A measuring system is presented, along with the results obtained. Considerations are made around the problem of automatic detection and some approaches are suggested. Finally, some conclusions are drawn from the work developed.

1. Introduction

Any variation to the knitting process needs to be investigated and corrected. Defects fall into this category since when they appear repair is needed, which is time consuming and sometimes results in fabric rejection.

The study of this problem has led to the identification of two main categories of defects in knitted fabrics: horizontal and vertical variations [1,2]. While the first category is mainly due to the yarn (quality and management), the second category is related with the knitting elements: needles, sinkers, feeders, and so on. The solutions encountered for solving these problems are, for the first category, a careful selection and management of the yarn, and for the second, the correction or substitution of the defective elements. In order to deal with these problems, various studies have been conducted and some specialised systems were developed, which can detect abnormalities in the yarn being fed, defects in the knitted fabric and defects in the knitting elements [1,3]. For the detection of yarn problems most systems will stop the knitting machine when the yarn input tension falls bellow some limits. The systems based on the detection of knitted fabric faults are basically photoelectric cells located very near to the fabric, inside or at one side of the machine cylinder. With the help of a lamp conveniently orientated, these systems detect holes and dropped stitches. The systems used for the surveillance of defective knitting elements are normally optical or capacitive sensors analysing, respectively, the shadow produced by the knitting element or the electric field variation produced by the elements, looking for broken needles, closed latches and broken sinkers. These systems are very effective and are capable to detect with high accuracy the position of the defect, stopping the knitting machine immediately, thus reducing loss. Unfortunately they are very specialised and usually do not give further information related with the knitting process and the cause of a defect. Furthermore some abnormalities pass through without being detected.

The proposed approach is based on yarn input tension analysis, which is a reflection of the whole knitting process for a given yarn feeder. By using this method it is possible to observe the whole process of loop formation, thus enabling the detection of abnormalities along with their position in the appropriate knitting element (ex. needle) and possible cause diagnosis.

2. Equipment

2.1 The Measuring system

The equipment used was a Tricolab sample making circular knitting machine, with a 3,75" cylinder, gauge 14 (corresponding to 168 needles) and one single feeder. It is equipped with a roller type positive feeding system and the yarn speed can be adjusted by means of a worm screw. A speed inverter, connected to the knitting machine's motor allows the adjustment of the cylinder speed with a coefficient of variation of 0.5% [4]. For the purpose of measuring the yarn input tension, a Rotschild tension meter was used, with a measuring range of 0-10 cN. An optical sensor is responsible for triggering the acquisition and sending a signal when a revolution is completed. The acquisition of the yarn input tension is made by means of an acquisition board from National Instruments, model LabPC+, to which both sensors were connected. This is a low cost board whose main features are eight A/D input channels, two D/A output channels, 24 I/O lines and two external timers. It's maximum sampling rate is 83000 samples per second (depending on the numbers of channels simultaneously used) and the maximum input range is 0-10 V.

The measuring system was modified so that aliasing was avoided and the output range of the measuring system was corrected to conform to the input range of the acquisition board. Voltage attenuation was performed resulting in the adjustment of 0-10 V range required by the acquisition board. In order to avoid aliasing, it was necessary to know with some detail the behaviour of the measuring system, which implied an evaluation of the static and dynamic characteristics. Besides the establishment of a linear relationship between tension and voltage, the calibration process permitted to know some other features of the measuring system, such as its accuracy and precision. The values measured indicate a good precision (1.2% Full Scale) and a fair accuracy (+5.8%, -0,3% F.S.).

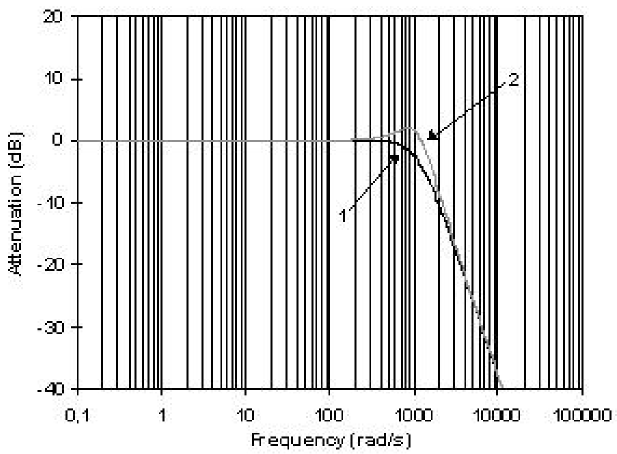


Figure 1. Frequency response of Rothschild tension meter

The study made pointed out that an overcharge was applied to the measuring system, since the largest difference of the real values is related to smaller forces. The dynamic response indicates how fast the measuring system will respond to transient signals, like the ones involved in the knitting process. The step response can give useful information, both in the time and in the frequency domains, in particular if the measuring system responds as a 2nd order system as it is the case. The sensor has a very rapid response. However, due to the underdamped adjustment, it takes some time to achieve a value considered to be the correct one, usually called the settling time (for 5% or 2%). On the other hand, the frequency response revealed that the sensor's w_r frequency is about 136 Hz. Figure 1 represents the ideal response (curve 1) and measured response (curve 2) for the tension meter. The measured response shows that this sensor should be used for measuring changes with a maximum frequency of about 90 Hz, in order to avoid overshoot and non-linear phase shift. This result means that the recommended cylinder speed should not exceed 0.15 ms^{-1}, in order to give correct readings. Above this value the sensor will behave like a low-pass filter, thus giving an average value of the signal and attenuation of its magnitude.

Considering that the signal acquired will have information for about three times the natural frequency of the sensor (which corresponds to 10% of the signal), it is possible to establish the cut-off frequency for the anti-aliasing filter, which is about 500 Hz. The implemented active filter has a cut-off frequency of 470 Hz and is based on a filter with equiripple error of 0.05º, with four poles. It was implemented using the biquad model with low sensitivity [5]. This solution allows reducing the frequency bandwidth to less than 500 Hz, enabling the acquisition of signals at twice the frequency, i.e. 1000 samples per second, without the danger of the signal being aliased [6].

2.2 Knitlab

In order to acquire, manipulate and store the information gathered during the experiments, an application was developed using LabVIEW 4.0, from National Instruments. Its main features are the graphical programming language, called G, a very fast learning curve which allows the development of the applications in a short period of time and the ideal integration with drivers and hardware, since they all come from the same manufacturer.

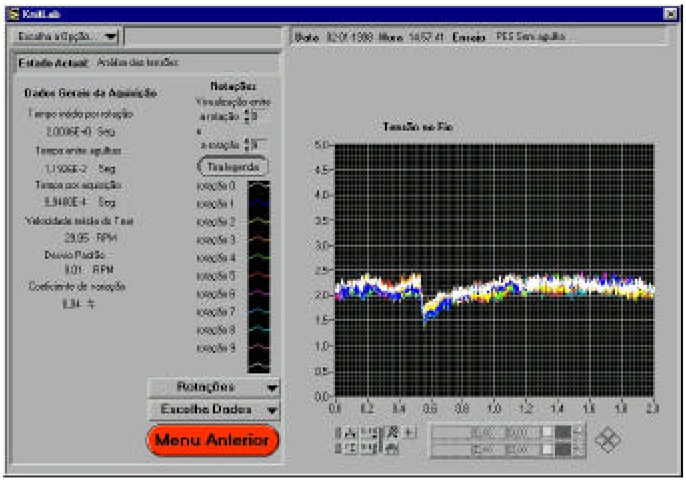


Figure 2. Visualisation module of the KnitLab Application

The application developed – KnitLab - can be organised in a few modules: configuration, acquisition, visualisation, storing and reading. Even though they are all important, the most useful are the acquisition and visualisation modules, which will be briefly described. The process of acquisition is very simple. After the adjustment of the knitting speed, the acquisition board waits for a signal from the optical sensor that indicates the starting point of a cylinder revolution and will trigger the acquisition. Then, the tension is acquired, stored, and simultaneously visualised on the screen. This process will terminate, either with a command from the user or as soon as a certain number of revolutions are accomplished. After this stage, the data acquired is organised in a 2D array in which each column represents a singular cylinder revolution. At this time, the program is ready to display the revolutions acquired, along with a set of statistical information related to the acquisition, such as cylinder speed, time elapsed between revolution and needles and so on. Figure 2 illustrates an experiment conducted for polyester yarn, displaying 10 revolutions produced with one missing needle. The visualisation module supports a set of tools which were considered as important for the analysis of the tension, such as the average, differentiation, digital filtering, frequency analysis and others. The remaining modules of configuration, storage and reading of data, allow modifications of some parameters used by the application and the saving of information from experiments to be analysed at a later stage. The files generated by the storing module can be used in other Windows applications, such as Excel.

3. Experimental

3.1 Planning

The experiment involved a set of situations to be simulated, which comprehend the type of defect, the tightness factor and the yarn nature. All the experiments were conducted at the same speed, 0.15 ms^{-1}, because of the sensor's limitations. The yarn used was polyester 240 dtex continuous filament (because of its regularity) and 100% cotton 24 Ne combed and carded. Loop length variation was realised by using the tightness factor (K) of 13, 15 and 17. The situations considered were a missing needle, a needle without its hook, a missing sinker, a needle without its latch, a damaged latch and the presence of a knot in the yarn. It is important to note that only one defect is present at any one time. The knit structure used was single jersey.

As stated earlier, the main objective of this work is the study of the waveform resulting from the yarn input tension, in order to evaluate the possibilities of detecting defects and malfunctions produced during the knitting process.

The analysis of the waveform obtained after the process of acquisition can be presented in two domains: time and frequency. The time domain allows the study of the entire waveform and the study of a window corresponding to the time elapsed to form a single loop. Characterisation and interpretation of the results are performed in both cases, in order to evaluate the various defect possibilities. A similar analysis is done in the frequency domain. However, the main goal in this case is to determine abnormal situations of the knitting process with a periodic nature.

The second stage involves the feasibility of using automatic methods for defect detection, and distinction. The analysis is performed for the time domain only and involves the two situations described in this section. For the waveform, a direct comparison between normal and abnormal functioning is performed and for the parameters considered in the loop analysis, a statistical tool is used in order to evaluate the possibility of considering a window with one single loop for defect identification.

3.2 Results

3.2.1 Frequency domain

The unique characteristics of a circular knitting machine can be explored through the use of spectral analysis. This may be used to pin point abnormal functioning of the knitting process, since problems related to components involved in the movement of the knitting machine and in the production of the knit fabric will be reflected in the yarn input tension.

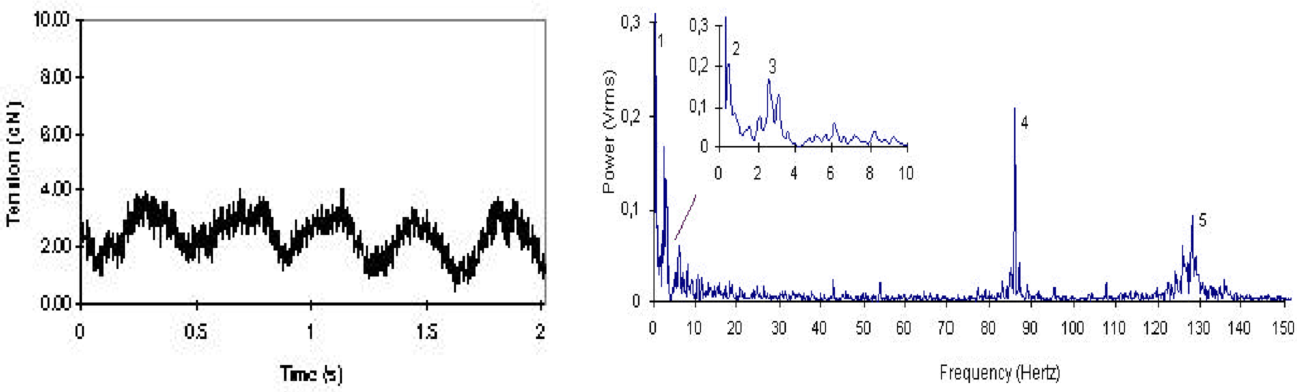


Figure 3. Abnormal feeding system functioning (a) and resulting spectrum (b).

As an example a simulated situation is presented. A positive feeding system with an eccentric roller will produce a periodic increase in the yarn input tension. This problem is illustrated in figure 3 where one can clearly see that the speed of the positive feeding system is about five times larger than the cylinder speed.

This abnormality can be identified in the resulting spectrum of the waveform by harmonic number 3, which gives an increased peak. Spectral analysis can thus be very useful in the identification of problems when these are not so clear in the time domain [4].

Harmonic	Frequency (Hz)	Meaning
1	0	Average Yarn Tension
2	0,5	Cylinder Speed
3	2,5	Feeding System Speed
4	84	Yarn Tension Variation
5	128	Sensor Wr Frequency

Table 1. Harmonics identified in the spectra.

The detection of defects by using this method is not clear, since the differences detected so far are insufficient to distinguish them. Moreover, this method does not allow the determination of the position of the defect, which may be a major disadvantage.

3.2.2 Time domain

The observation of the waveform resulting from normal knitting and for situations derived from the presence of defects gave very interesting results. The production of knitted fabric with no defects reveals a typical waveform with characteristic limits for each kind of yarn, being larger for cotton, probably because of its natural irregularity. It is possible to observe a little increase for the same limits when the tightness factor is considered. For instance, with the polyester yarn a typical standard deviation of the yarn input tension is 0.14 cN when K=13, 0.16 cN when K=15 and 0.21 cN when K=17. This effect could be due to the increase in the force needed to pull the new loop through the old one [4].

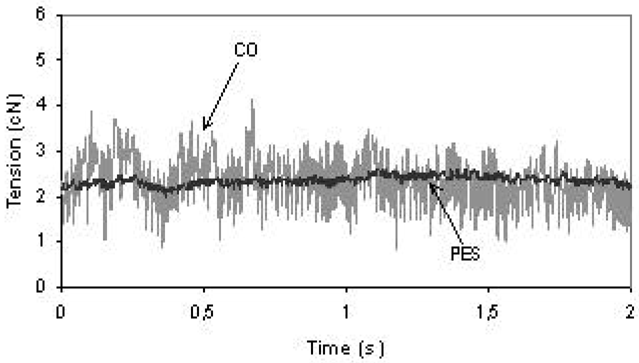
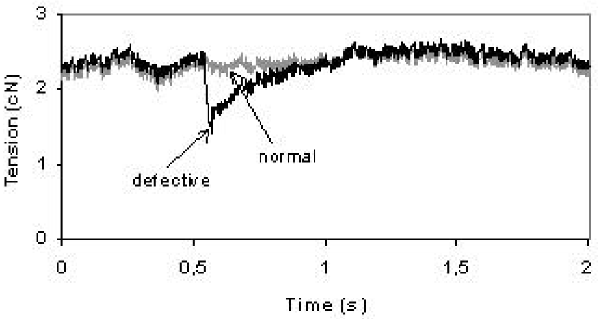
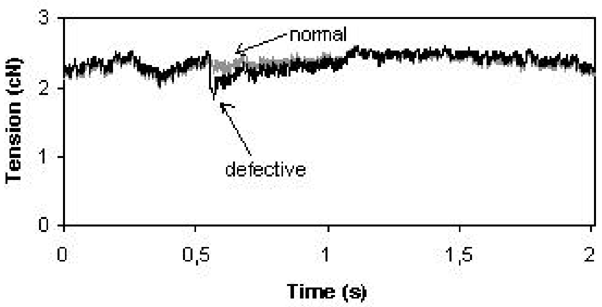


Figure 4. Waveforms for polyester 240 dtex yarn and combed cotton 24 Ne yarn.

In the set of defects considered, there are two waveforms that present similar shape: the lack of a needle and a needle without a hook. This result was predictable since the effect is basically the same: with no needle or no needle hook, the yarn will not be pulled, thus resulting in excess yarn, as shown in figure 5 and 6a. The excess yarn is then absorbed by the following needles, thus the average waveform is recovered some needles later, due to robbing back [7,8].



(a)

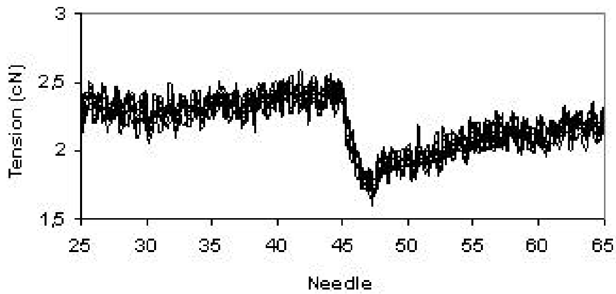


(b)

Figure 6. Two examples of defects simulated for polyester 240 dtex yarn: a) needle without hook, and b) no sinker.

The simulation of defects as resulting from observable differences when compared with the waveform obtained with normal knitting conditions suggests the possibility of quantification of these differences. Moreover, when there are differences between defects their location is easily determined, with a typical accuracy of about two needles and an excellent precision, as can be seen in figure 5.

From the experiments, it has been observed that variations between revolutions have a random behaviour. Figure 6 illustrate two distinct situations for the polyester 240 dtex yarn: no needle hook and no sinker.



5. details for 10 revolutions: resultant waveform of a needle without its hook.

The waveform resulting from the lack of a sinker presents a little excess of yarn in the region near the fault, resulting in a decrease in yarn tension (not so large as for a needle without a hook). The average value is restored more rapidly than for the case of a needle without a hook (Figure 6 b).

All abnormal situations have resulted in a decrease of yarn input tension and excess of yarn in that region. The only exception registered is for a knot in the yarn. This defect is characterised by a succession of rapid and gradually decreasing variation of yarn input tension, which is the result of the passage of the knot in the measuring head.

The behaviour so far described for the defects simulated will also appear in other types of yarn used in the experiment and do not seem to depend significantly on the tightness factor.

3.2.3 Measurement of the Differences

The differences observed when comparing a normal knitting waveform with a waveform resulting from a defect occurring were quantified by means of a performing measure of the knitting machine. This measure is based on the sum of the square differences (SQD) between the normal waveform and the last revolution performed by the knitting machine [4]:

$$SQD = \sum_{i=0}^{2015} \left(y_i - \frac{1}{100} \sum_{j=1}^{100} x_{ij} \right)^2$$

where y_i stands for point i of the latest acquired waveform and x_i stands for point i of the normal knitting waveform. It should be noted that the normal waveform was obtained by using the average of one hundred revolutions of the knitted machine when producing a faultless knitted fabric, as the expression show.

Using this measure for the simulations described in section 3.1 lead to table 2, which quantifies the difference observed between normal and defective knitting, for K=13 and 15.

From table 2 it can be suggested that there is some difference between normal and abnormal knitting. In fact, ANOVA tests were performed and their results have shown that the hypothesis of equality of means can be rejected, with a significance probability below 0,001 [10,11]. However, multiple comparisons Tahmane T2 tests showed equality of means for some cases, as illustrated in table 3.

	K=13		K=15	
	$\overline{X}_{SQD}$	S_{SQD}	$\overline{X}_{SQD}$	S_{SQD}
Normal	9.84	2.43	12.65	3.64
No Needle	38.98	5.52	32.49	8.15
No Hook	36.78	6.65	36.06	6.88
No Latch	15.71	3.48	25.47	6.78
No Sinker	14.72	3.64	20.91	5.57
Damaged Latch	24.37	7.36	39.53	6.87
Knot	27.01	7.13	26.90	6.30

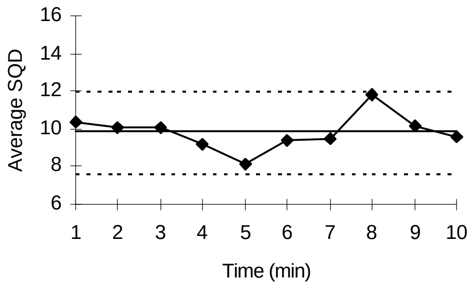
Table 2. SQD values for polyester 240 dtex yarn.

K=15 / K=13	Normal	No Needle	No Hook	No Latch	No Sinker	Dam. Latch	Knot
Normal	-	0.000	0.000	0.000	0.000	0.000	0.000
No Needle	0.000	-	0.007	0.000	0.000	0.000	0.104
No Hook	0.000	0.259	-	0.000	0.000	0.038	0.000
No Latch	0.000	0.000	0.000	-	0.007	0.000	0.991
No Sinker	0.000	0.000	0.000	1.000	-	0.000	0.022
Dam. Latch	0.000	0.000	0.000	0.000	0.000	-	0.000
Knot	0.005	0.049	0.130	0.038	0.033	0.993	-

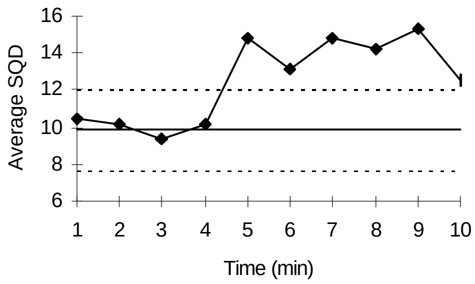
Table 3. Multiple comparisons tests for SQD mean values and corresponding significance probabilities.

The equality for some of the cases was expected, such as for missing needle and no needle hook, because the waveform generated for each of them had a similar shape. However, for situations like the lack of a sinker and the lack of a latch, the equality of means wasn't expectable, since these defects are different. The worst case is the presence of a knot. This situation can be misinterpreted with some of the other situations simulated. In spite of all these problems, one can say that none of the situations can be confused with normal functioning, so this measure can still be used to detect malfunctioning of the knitting machine during fabric production [4].

The SQD measure assumes particular importance if it is used on control charts. A control chart represents a graphical method for testing hypothesis continuously, there existing several types of charts, each relating to a characteristic being measured. By using a control chart one can monitor the production process, and detect any problem concerned with it.



(a)



(b)

Figure 7. X-chart for knitting production: a) normal functioning; b) a problem with the knitting process.

Figures 7 represents a X - chart for a simulation of normal knitting (a) and a situation where a problem has been detected (b). The simulation was performed with the knitting machine working at 0.15 ms^{-1} and for polyester 240 dtex yarn. Each point plotted on the X control chart represents the average of 10 SQD measures taken per minute, even though it would be possible to represent all the revolutions performed during one minute. The recommended value of SQD for the process being measured is around 9.84 for normal knitting. It is possible to observe that for the situation shown in figure 7 a) the process can be considered as under statistical control [12]. However, for the situation shown in figure 7 b), a problem has been detected in minute 5, since the value assumed by the SQD has increased considerably and came out of the control limits, giving a new average value for the SQD. This is due to a problem detected that remained without repairing. Unfortunately, as shown previously in this section, this technique does not permit to distinguish and locate the problem which may be due to the lack of a sinker or a broken needle latch. In fact, the defect simulated was due to a broken latch. The positioning of the cause of this defect could be determined by analysing the corresponding waveform.

3.2.4 Distinguishing defects

The information obtained from the yarn input tension allows to go a little further and study the behaviour of the tension in the production of a knitting stitch. Figure 8 illustrates a typical waveform for loop formation.

Legend:
T_i = Yarn input Tension;
$T_{i\,min}$ = Minimum T_i;
$T_{i\,a}$ = Mean T_i;
$T_{i\,max}$ = Maximum T_i;
a = Beginning of yarn feed;
b,d = Point where $T_{i\,a}$ occurs;
c = Point where $T_{i\,max}$ occurs;
e = Point where $T_{i\,min}$ occurs;
t_{max} = Time elapsed from point a to point c;
t_{min} = Time elapsed from point a to point e;
Δt = Time elapsed form point b to point d;
S1 = Slope for tension increase;
S2 = Slope for tension decrease.

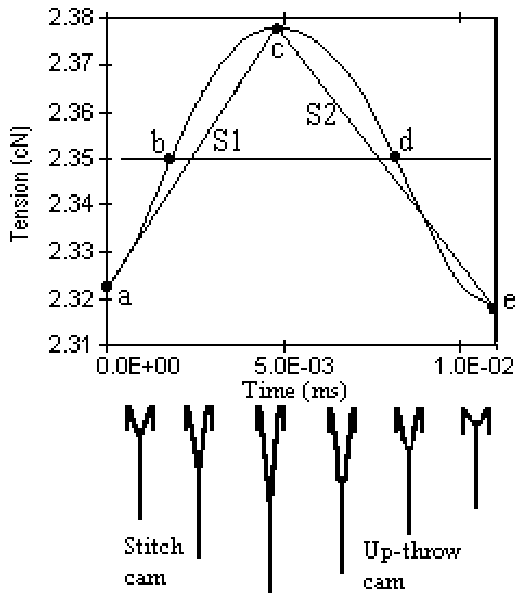


Figure 8. Typical shape of yarn input tension for stitch formation, for polyester yarn.

The variation of yarn input tension depends on the needle position in the knitting cycle. It should be maximum at knock over and minimum at clearing and normal running position, as shown in figure 8. In normal knitting conditions the waveform has this shape, even though some variability may be expected that can be explained by yarn characteristics, such as friction [8,9], and the variation related to the individual knitting elements.

This typical shape can be characterised by a few parameters and one could try to use it to distinguish the situations simulated. The parameters used are illustrated in figure 8 and are resumed for the situations described in table 4, for polyester 240 dtex yarn, K=13 and a knitting machine speed of 0.15 ms^{-1}.

This information was obtained from several revolutions acquired from the production of jersey fabric, concerning the situations simulated. Cluster Analysis was performed in order to evaluate the possibility of automatically distinguishing defects and to evaluate if this statistical method will correctly classify the cases pertaining to a situation as grouped in the same cluster. The results were obtained by using Ward method for grouping and the Euclidean quadratic distance as the proximity measure [10,11].

Parameter	Normal	No needle	No Hook	No Sinker	No Latch	Damaged Latch	Knot
Average	2,389	2,022	2,080	2,486	2,173	1,855	2,178
Maximum	2,444	2,411	2,438	2,539	2,363	2,010	2,341
Minimum	2,339	1,767	1,843	2,440	2,070	1,778	2,034
T between average	0,000	0,000	0,000	0,003	0,000	0,000	0,005
Traising (0% to 100%)	0,007	0,001	0,001	0,005	0,001	0,001	0,005
Tfalling (100% to 0%)	0,003	0,012	0,012	0,002	0,012	0,012	0,001
Raising slope	14,902	0,000	0,000	18,428	0,000	0,000	61,384
Falling slope	-7,017	-53,659	-49,598	-16,988	-24,457	-19,367	0,000
Max. Pos.	0,010	0,001	0,001	0,011	0,001	0,001	0,012
Min. Pos	0,004	0,012	0,012	0,001	0,012	0,012	0,008

Table 4. Parameters used to characterise the yarn input tension for loop formation.

Table 5 summarises the Cluster Analysis performed and the clusters obtained for the solution suggested and respective percentage of elements for each situation grouped in the same cluster. From the number of situations simulated, one should expect six clusters, but the result presented five clusters only from which four are valid, since the last cluster is formed by cases which are not different enough to be considered to pertain to the expected cluster. The interpretation of the clusters can, however, explain this behaviour.

Cluster	Case (percentage of cases in cluster)
1	Normal (85%), No Sinker (90%)
2	No Needle (95%), No Hook (95%), No Latch (80%)
3	Damaged Latch (95%)
4	Knot (25%)
5	Others

Table 5. groups obtained with cluster analysis.

Cluster number one groups *Normal* knitting with the situation of *No sinker*. This grouping has happened because the defect simulation was always performed in the same position in the knitting machine, i. e. needle 46 (or the sinker after it).

Cluster number two groups three situations: no needle, no needle hook and no needle latch. In spite of the grouping of the first two situations which was predictable, the last situation was not expected to be in this cluster. The fact that it is, is due to the similarity of the shapes between the three situations, as can be seen in table 4. However, it was expected that the difference in magnitude would be large enough to distinguish this case form the other two. The remaining clusters were well judged.

In terms of the accuracy of grouping all cases pertaining to a situation in the same cluster, one could say that only for the presence of a knot the percentage is very low. This is due to significant differences measured between the cases inside this group. The other situations have more similarities inside their own groups, which is reflected by the high percentage of cases from a given situation correctly classified in the same cluster. This result also means that the variability inside the groups representing the situations simulated is low enough to allow the use of a statistical tool for grouping them in the same cluster.

4. Conclusions

Defect detection by inspection of the yarn input tension appears to be a valid approach. The study presented in this work showed that the typical waveforms resulting from normal and abnormal knitting are different and can be quantified. In fact, the presence of a defect could be detected, identified and located with high accuracy, which constitutes a major step in reducing repair time. The results obtained through the application of statistical tools in one case and direct comparison in other, suggest that it is possible to detect and distinguish the defects by other means than by observation. The use of control charts can be a valuable tool for evaluating the knitting machine's general working conditions. However, further study needs to be conducted in order to determine other measures and characteristics capable of best detecting the differences between the defects simulated in a more precise way.

The versatility of this technique is excellent, since it is possible to use several different tools, such as spectral analysis and control charts, to determine and detect a set of problems that other monitoring systems cannot offer.

Further studies are being developed, both in a new measuring system that will allow to measure the yarn input tension at higher speeds and also in methods for detecting and distinguishing defects.

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