DEVELOPMENT OF A NOVEL TYPE OF ONLINE MONITORING SYSTEM FOR THE BRAIDING PROCESS

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Keywords: braiding, braiding defects, online process monitoring

Abstract

A new cost-efficient sensor module for the detection of thread tension anomalies in braiding machines was developed. The sensor module is mainly attached to the body of the braiding machine (bobbin carrier independent) and works by contactlessly detecting the position of the lever of the yarn tensioning mechanism of the bobbin carriers through magnets and stationary Hall effect sensors as the bobbins pass by. This way, time-discrete estimations of the tension of the moving braiding yarns in a braiding machine can be calculated.

Validation experiments of the module on a stationary test stand which simulates the unwinding process during braiding were conducted. Flawless reference measurements revealed that the signals from the Hall probe are in good agreement with precise yarn tension measurements obtained simultaneously from a deflection roller based yarn tension measurement device. Further measurements with purposefully provoked unwinding-related irregularities showed that braiding defects are foreshadowed by prominent variations in yarn tension. For carbon fibre yarns, the sensor module detected an unusual rise in yarn tension at least by the time 510 mm of yarn remained to be unwound from the bobbin until the final yarn breakage occurred. Thus, the sensor module is capable of identifying irregularities soon enough before major braiding defects evolve. However, the lead times were significantly shorter when investigating polyester yarns. If a high detection reliability is required for this kind of material, the number of sensors needs to be increased or additional sensor modules have to be put in place.

1. Introduction

The quality of braided textiles from reinforcement fibres and the stability of the process are negatively affected by irregularities that occur during braiding. Since irregularities can lead to braiding defects which cause material waste and machine downtime, machine productivity is reduced and additional costs for error cause analysis and error correction time arise. Previous investigations conducted by Ebel et al. [1] have shown that braiding defects are often induced by a small cause and evolve through various stages to a major failure event. The more advanced a defect is when it is detected, the higher the aforementioned additional error costs are. Thus, the development of an online monitoring system for the braiding process which is able to detect the evolution of braiding defects already in early stages is highly desirable.

Mierzwa et al. delineated in [2] that a specific effect named fibrous ring was the most critical braiding irregularity during their unwinding and braiding experiments with a 24k HT carbon fibre yarn (1650 tex, 0,3 wt% of epoxy sizing). This effect is described as a ring-shaped accumulation of carbon filaments which impedes the yarn from unwinding from the bobbin. It origins primarily from yarn predamage and partly from unsuitable rewinding parameters. The consequential braiding defects in the experiments were an up to 4 mm wide gap in the preform – which leads to an optical damage and a deterioration in mechanical properties – or a breakage of the yarn. Apart from gaps in the preform and yarn breakage, Ebel et al. [3] also mentioned loops in the preform due to a loss of yarn tension as a typical braiding defect. However, they pointed out that especially the occurrence of yarn breakages as a result of the formation of fibrous rings significantly reduces the productivity of a braiding machine. In their endurance braiding tests, which were performed on an axial braiding machine with 60 carriers, a horn gear diameter of 120 mm and a horn gear speed of 120 rpm, they manufactured triaxial hoses with glass fibre as braiding yarns (braiding angle: 45°) and carbon fibre as UD yarns. They observed a machine downtime of up to 26 % of the total production time due to the necessity of manually repairing or rethreading yarns which had broken due to fibrous rings. However, Ebel explains in his work [4] that in a production environment with trained workers, this portion of machine downtime may be lower compared to the investigated research environment.

2. Existing Systems for Process Irregularities Detection during Braiding

In order to avoid the effects of braiding defects described above, some sensor systems for the monitoring of the braiding process already exist. On the one hand, there are systems which make use of tactile sensors that are stationary attached to the body of the braiding machine (bobbin carrier independent systems). On the other hand, there are approaches which include the installation of sensors onto the bobbin carriers (bobbin carrier dependent systems).

One of the commercially available bobbin carrier independent systems comprises rudimentary switches which jut into the tracks of the bobbin carriers. These switches are activated by extensions of the levers or sliders which are part of the yarn tensioning mechanism of the bobbin carriers when a total loss of yarn tension arises (cf. Figure 1). Such a system may serve as a trigger to stop the braiding machine on occurrence of a yarn breakage to avert the production of a braid with loose or missing yarns. An advantage of such a system is its simplicity and cost-efficiency. However, this kind of system causes a considerable amount of machine downtime because it only responds when a yarn has already broken. Due to the above-mentioned necessity of manually repairing or rethreading yarns after a breakage has occurred, resolving a braiding process defect in this final stage is much more labour intensive than in earlier stages like gap formation due to a moderate increase in yarn tension. The latter defect can in most cases simply be resolved by removing a fibrous ring on the respective bobbin.

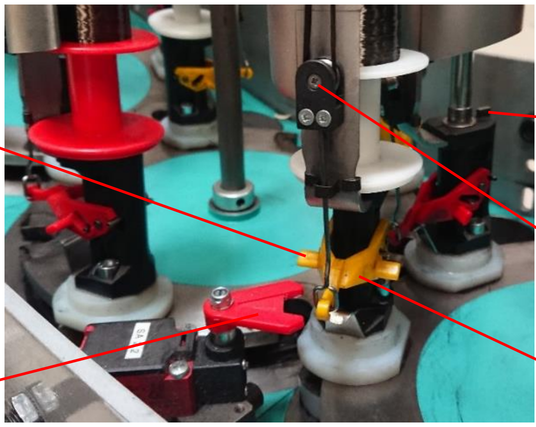

Figure 1. Rudimentary switch jutting into track of bobbin carriers

Another bobbin carrier independent system invented by Lenkeit [5] makes use of a force sensor with a skid attached to it. The sensor and its skid are arranged between the plane spanned by the uppermost thread guiding elements of the bobbin carriers (indicated in Figure 2) and the braiding point in a way that the yarns periodically touch and slide along the skid of the force sensor as the bobbins travel through the braiding machine along their closed tracks. In doing so, the skid deflects the yarns by a defined angle. Hence, the tension of each thread can be calculated from the force measured by the sensor at discrete time intervals. Such an arrangement can detect process irregularities that result in a variation in yarn tension before a thread has already broken. Nonetheless, a major drawback is the yarn damage that is caused when the yarns touch the skid at high speed. This point is particularly relevant when processing carbon fibre yarns which consist of thin, brittle filaments.

An example for a bobbin carrier dependent sensor system is provided by Reuter et al. [6]. They mounted a load cell onto a single bobbin carrier of a radial braiding machine RF 1/144-100 from Herzog GmbH (cf. Figure 2). Thereby, the load cell was located between the 180° deflection pulley and the lever of the yarn tensioning unit of the bobbin carrier. Moreover, they fitted a telemetry device onto the bobbin carrier which united the functions of an energy supply, a voltage regulation, an analog/digital converter and a wireless transmission.

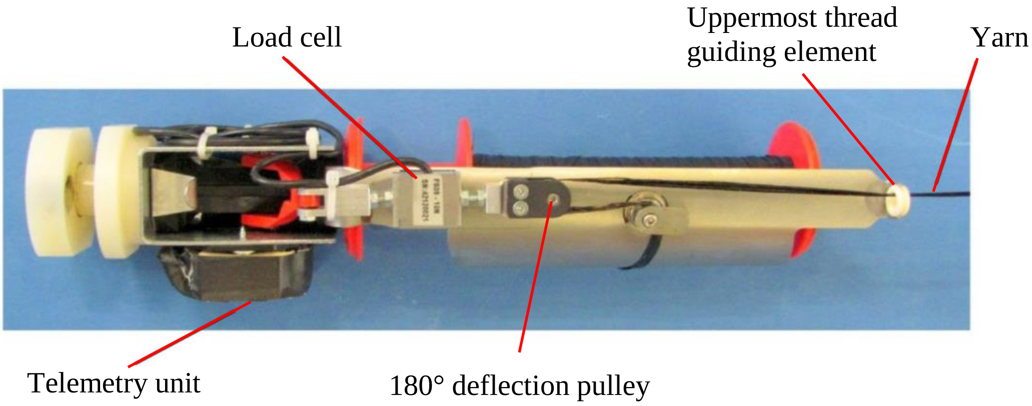

Figure 2. Load cell and telemetry unit mounted onto a bobbin carrier; image taken from [6]

Braeuner [7] designed a whole new bobbin carrier with a slide that is displaced by the yarn tension against a resilient element. The yarn tension is determined by sensing the position of the slide along its track on the bobbin carrier. Furthermore, Braeuner's invention also comprises a communication module and an actively driven material buffer so that the yarn tension can be controlled wirelessly while the braiding machine is running. Both of these bobbin carrier dependent systems are able to measure the yarn tension during the braiding process very accurately and are therefore capable of detecting irregularities at short response times. Major drawbacks of this kind of systems are however the comparatively high costs for energy supply units, sensor and communication hardware as well as the effort it takes to install the hardware on all bobbins (up to several hundreds) of a braiding machine.

Conscious of the existing sensor systems and their inherent strengths and weaknesses, we are currently working on an online monitoring system for the braiding process which is cost-efficient on the one hand while being sufficiently precise to determine unusual variations in yarn tension on the other hand. Furthermore, the system shall be on a modular basis so that it can be used in the production of a broad spectrum of products ranging from mass goods such as shoelaces (trimmed-down version of the monitoring system) to high performance carbon fibre reinforced composite parts (full version of the monitoring system). The aim is to be able to predictively stop the braiding machine before process irregularities lead to yarn breakage and consequently to labour intensive error correction. The first sensor module of the system in development with its measurement principle and early validation experiments are depicted in the paper at hand.

3. New Concept for Thread Tension Anomalies Detection during Braiding

During operation of the braiding machine, the bobbin carriers are moved through the machine by rotating horn gears along closed, intersecting tracks. At the same time, yarn is tangentially unwound from the bobbins. If the yarn tension drops below a desired value, a thread tensioning unit at each bobbin carrier prevents the bobbin from rotating around its central axis by means of a locking pin (viewable in Figure 1) which engages with lateral notches in the bobbins. As more yarn is pulled by the braiding machine, the yarn tension increases. Two times the unwinding yarn tension plus a frictional component is applied to the lever of the yarn tensioning unit by a 180° deflection pulley (cf. Figure 1, Figure 2 and Figure 3). This way, the increasing yarn tension lifts the lever against a spring incorporated inside the bobbin carrier until the release force is reached. At this point, the lever retracts the locking pin. The given yarn tension then causes the bobbin to rotate around its central axis and yarn is unwound from the bobbin. This in turn leads to another drop in yarn tension which causes the lever to move downwards and reengage the locking pin. During braiding, cycles of engaging and disengaging the locking pin according to the given yarn tension succeed each other.

The newly developed sensor module for the detection of thread tension anomalies makes secondary use of the above-depicted and already existing yarn tensioning unit of each bobbin carrier as a kind of spring balance. Thereby, the number of required additional components is reduced. To measure the thread tension as the bobbins travel through the machine, the position of the lever of the yarn tensioning unit is detected by the new sensor module. For this, the module comprises magnets which are mounted onto the levers of the yarn tensioning units of the bobbin carriers, Hall effect sensors which are stationary attached to the body of the braiding machine and an Arduino microcontroller as a computing device. Additionally, LEDs as a visual indicator to mark the position of an anomal bobbin carrier to maintenance personnel were arranged near the braiding machine. As magnets, permanent, cylindrical neodymium magnets with a diameter of 8 mm, a height of 3 mm, an energy density of approximately 342-366 $\frac{kJ}{m^3}$ and a maximum service temperature of 80 °C (quality class N45) were used. In order to reduce their susceptibility to corrosion, the magnets were coated with an epoxy resin film. Firstly, the magnets need to be attached to the yarn tensioning units of the bobbin carriers. For this, a single magnet is pressed into a recess in a 3D printed housing (cf. Figure 3). The housing in turn features a slot so that it can tightly be pushed onto the extension of the lever of the thread tensioning unit of the bobbin carriers. For a more elaborate version than the prototype described herein, a lever of the thread tensioning mechanism with an integrated magnet is conceivable. Secondly, the Hall probe (an Iduino SE022 analog Hall sensor module) needs to be held in place by a 3D printed, height-adjustable fixture in such a way that it is able to detect the magnetic flux density of the field created by the magnet that is attached to the lever of the yarn tensioning unit. Due to the fact that this lever is rotatably placed to the bobbin carrier, the distance between the magnet and the hall probe as well as the orientation of the magnet to the probe alter with varying yarn tension. Hence, the analog signal from the hall probe is a non-linear function of the yarn tension. The corresponding mapping function can be obtained from experiments.

Every time a bobbin carrier passes by the stationary sensor, the corresponding yarn tension can now contactlessly be determined by applying the mapping function. Since the sensor is arranged next to the closed track along which the bobbin carriers are travelling during operation of the braiding machine, a single sensor may serve to determine thread tension anomalies of all bobbins on one track. Due to the fact that there are two of these closed tracks with opposite directions of bobbin movement in a braiding machine, at least two Hall sensors are required to monitor all braiding yarns of a machine. However, the system can only measure the corresponding yarn tension of a bobbin in discrete time intervals. If multiple sensors are arranged along the track, ”blind spots” can be reduced and along with that the overall response time of the system can be improved. Certainly, all sensor fixtures need to be adjusted to exactly the same height in this case to generate comparable sensor signals. Reference measurements with the sensors installed into an RF 1/128-100 braiding machine from Herzog GmbH while the machine was running have already been conducted. However, for reasons of space and due to the preliminary character of these measurements, they are not further elaborated in this paper.

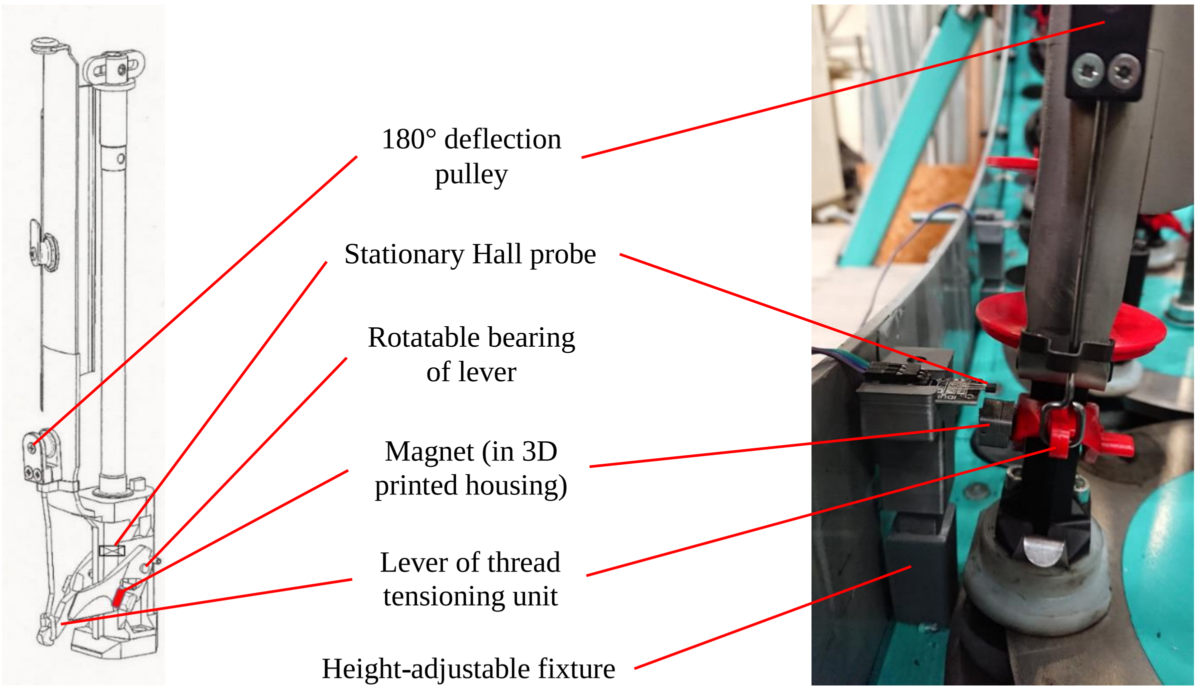

Figure 3. Drawing (left) and image (right) of the arrangement of magnet, Hall effect sensor and bobbin carrier with its yarn tensioning unit

To conclude this chapter, it is to note that the measurement principle described above can be applied to radial as well as axial braiding machines as long as their bobbin carriers comprise a spring based thread tensioning unit. Other sensor types such as optical, acoustic or inductive sensors to determine the position of the lever of the thread tensioning unit were also considered. The given requirements regarding precision and especially costs were, however, best met by the chosen approach via magnets and Hall effect sensors.

4. Validation Experiments of the Sensor Concept

Mierzwa et al. [2] used an unwinding test stand to simulate and to closely study the unwinding process during the braiding process. In order to validate the new sensor module, the stationary bobbin carrier of the very same unwinding test stand was equipped with the components of the senor module mentioned above (housing for magnet, neodymium magnet, height-adjustable fixture and Hall probe). Furthermore, a self-constructed rotary position transducer was added to keep track of the length of the yarn that is being unwound as well as to precisely adjust the unwinding speed. The test stand works as follows: A NEMA-23 bipolar precision stepper motor with a 15:1 gear box from Phidgets Inc. winds the yarn onto a reel, thereby unwinding it from a bobbin which is located on a stationary bobbin carrier. The unwinding process is recorded by an SLR camera, the position of the lever of the thread tensioning unit is determined by the Hall sensor and the yarn tension is measured by a load cell mounted onto a 90° deflection roller (M1391 from Tensometric Messtechnik GmbH). The data is acquired using a USB-6009 data acquisition device from National Instruments and MATLAB R2015b.

Three different yarn materials were investigated, as there are: a double folded polyester (PES) monofil yarn with a diameter of 0.25 mm, a double folded PES multifilament yarn with a titer of 300 tex of the individual yarns and a carbon fibre yarn of the type Tenax®-E HTS40 F13 12K with a titer of 800 tex.

All of the three yarns were tested repeatedly at unwinding speeds of 40 $\frac{mm}{s}$ and 80 $\frac{mm}{s}$, respectively. To keep the duration of a single test at about 20 minutes, 50 m of yarn were wound onto the bobbins for the configurations with the lower and 100 m of yarn were wound onto the bobbins for the configurations with the higher speed. Moreover, all configurations of yarn material and unwinding speed were investigated with a compression spring of the yarn tensioning mechanism with a release force equivalent to a mass of 350 g. Additionally, the PES monofil was tested with a 130 g-spring and the PES multifil as well as the carbon fibre yarn were analysed with a 700 g-spring. Finally, reference measurements with each configuration to study the behaviour of the yarn materials when they are unwound flawlessly as well as measurements with provoked irregularities were conducted.

The first question that needed to be answered by the validation experiments was if the measurements from the cost-efficient sensor module described in the previous chapter were in reasonable agreement with the measurements obtained from the deflection roller based yarn tension measurement device. Exemplary measurement results of yarn tension and voltage of the Hall sensor of a flawless test with the carbon fibre yarn are shown in Figure 4. The figure reveals that the periodic fluctuations in yarn tension with the higher frequency – created by the yarn tensioning unit of the bobbin carrier and determined by the deflection roller based yarn tension measurement device – are well represented by the Hall sensor module. In addition, the superimposed fluctuation in yarn tension with the lower frequency equivalent to the rotation frequency of the bobbin – presumably caused by the central axes of the bobbin and bobbin carrier not being perfectly straight – is captured by the Hall sensor. Measurements with other materials and unwinding parameters confirmed these findings.

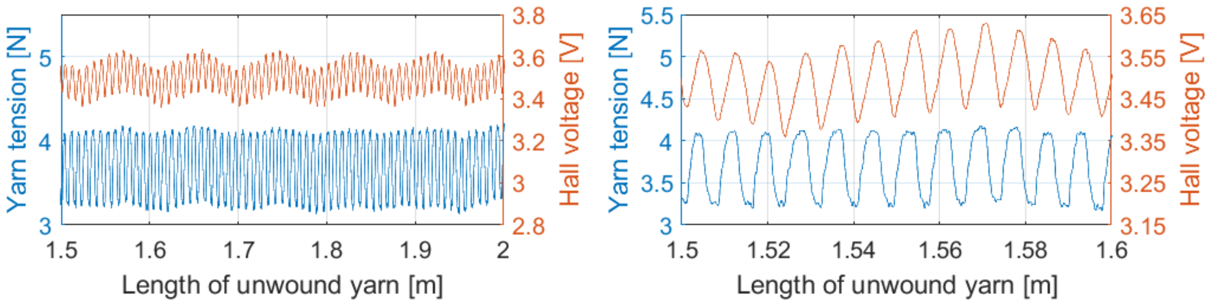

Figure 4. Overview (left) and detailed view (right) of a measurement of a pristine carbon fibre yarn at 40 $\frac{mm}{s}$ unwinding rate and 350 g-spring

The second question that had to be addressed was if the sensor module, when integrated into a braiding machine, was capable of detecting unwinding related braiding process irregularities soon enough before defects have reached their final stage (yarn breakage). In order to clarify this issue, flaws were purposefully introduced into the yarns. Similar to the procedure introduced by Mierzwa et al. [2], the carbon fibre yarn was predamaged during the rewinding step with sand paper with a particle size of 800 Mesh. This reinforces the tendency of the yarn to form fibrous rings during unwinding. The double-folded PES multifil was rewound onto the bobbins with diverging yarn tensions of 3.8 N and 8.0 N (determined by a portable yarn tension measurement device of the type DTMX-500-U from Hans Schmidt & Co. GmbH). Shortly before the unwinding test, the yarn with the lower tension during rewinding was unwound one revolution from the bobbin while the other yarn remained unaffected – a flaw that can be introduced by maintenance personnel when replacing an empty bobbin in a machine, for example. The double-folded PES monofil was rewound at diverging yarn tensions only, namely 4.6 N and 12.1 N. In a production environment, only slight yarn tension differences occur. However, with several kilometres of yarn being wound onto a bobbin, even small differences in yarn strain can accumulate to large differences in yarn length. The extreme manipulation procedures cause both of the PES yarns to reliably develop loops at the bobbin during unwinding at the test stand. Eventually, the loops become knotted and impede the unwinding process.

A simple, hypothetical trigger criterion for the sensor module was then formulated: As soon as a Hall sensor detects a lever of the thread tensioning unit of a bobbin carrier in a running braiding machine which is in its uppermost position, the corresponding bobbin is considered to show a process irregularity. The idea behind this criterion is as follows: During braiding, the machine constantly pulls the yarn. The yarn tension ultimately reaches the release force of the spring of the bobbin carrier, the locking pin is retracted, the bobbin is then free to rotate and yarn can be unwound. Consequently, the yarn tension must drop and the lever of the yarn tensioning unit also moves to a lower position. If an unwinding-related irregularity occurs, the yarn cannot be unwound properly from the bobbin, although the locking pin is retracted. Since the braiding process goes on, the machine keeps pulling the yarn. Therefore, the yarn tension increases even more, causing the lever of the yarn tensioning unit to move further upwards than the point of the release force. This position of the lever beyond the point of the release force (lever deflection) occurs when an irregularity is present. Figure 5 shows an exemplary measurement of an unwinding test conducted with a carbon fibre yarn with a provoked fibrous ring. Prominent rises in yarn tension precede the final yarn breakage. The rises in yarn tension are accompanied by lever deflections that are detected by the Hall effect sensor.

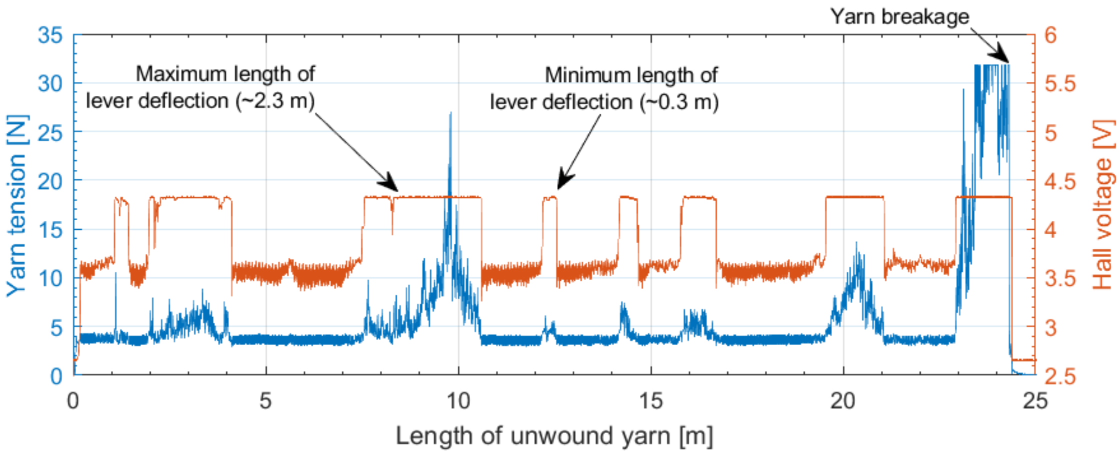

Figure 5. Measurement of a predamaged carbon fibre yarn at 40 $\frac{mm}{s}$ unwinding rate and 350 g-spring

The unwound lengths of yarn from the bobbins when the lever was detected in its uppermost position were analysed for all tests with provoked unwinding irregularities. The condensed results of this analysis are depicted in Table 1. For reasons of space, the detailed results concerning the influences of unwinding speeds and release forces of the compression springs are not discussed herein. The table shows that there is a considerable number of lever deflections which foreshadow a yarn breakage or an overload of the stepper motor. Since the sensor module only acquires time-discrete estimations of the yarn tension, it is crucial to know how long in terms of unwound yarn length the lever deflections last. The table shows that there are in fact very short, and therefore almost undetectable, minimum lever deflections (1-2 mm) for all of the three yarn materials. However, the significantly higher mean values of the unwound yarn lengths during lever deflections suggest that most of the deflections are detectable by the sensor system. This statement is underpinned when regarding the mean cumulated length of unwound yarn – a measure for the likelihood that any lever deflection of a moving bobbin carrier is detected by a stationary sensor. It says that there is on average at least 1.1 m of yarn unwound from a manipulated bobbin when the lever of the yarn tensioning mechanism is deflected upwards. Nevertheless, the overall minimum of the longest lever deflection per test indicates that the stationary sensors may not always predictively detect all major braiding defects. With this key figure being in the range of about 0.5 m for carbon fibre and considering typical circumferences and fibre angles of braided carbon composite parts, a single sensor per track is expected to work very well in the detection of fibrous rings. This is because the length of the yarn unwound from a bobbin during a full circulation through the machine is in most cases less than the determined lead time. However, the detection of loops, particularly loops of the double-folded PES multifil, is not fully guaranteed since the lead time in terms of unwound yarn length was – in the worst case measurement – only 13 mm.

Table 1. Analysis of lever deflections during unwinding tests

Material		*Carbon*	*PES multifil*	*PES monofil*
Number of specimens		20	24	20
Number of yarn breakages / stepper motor overloads		20	20	20
Mean number of lever deflections per test		5.5	20.8	3.5
Unwound yarn length during single lever deflection [mm]	Min	1	1	2
	Mean	1038	100	522
	Max	4362	1351	6655
Cumulated unwound yarn length during all lever deflections per test [mm]	Min	510	13	47
	Mean	4753	1685	1101
	Max	14058	4363	6691
Overall minimum of unwound yarn length during longest lever deflection per test [mm]		510	13	47

5. Conclusion and Outlook

The development of a first sensor module as part of a larger, comprehensive sensor system for the braiding process was presented. The sensor module is bobbin carrier independent and works by contactlessly detecting the position of the lever of the yarn tensioning mechanism of the bobbin carriers through magnets and Hall effect sensors as the bobbins pass by the sensors. This way, the module enables calculating the yarn tension of braiding yarns in discrete time intervals. Validation experiments on a stationary test stand with carbon fibre yarns, a double-folded PES multifil and a double-folded PES monofil were conducted. The experiments with several spring release forces and unwinding speeds as variation parameters proved that the detection of the position of the said lever by means of the sensor module provides a good estimation of the yarn tension. Furthermore, braiding irregularities were purposefully provoked by incorporating flaws into the bobbins that cause irregularities which hamper the unwinding process. The results on the mean cumulated unwound length of the yarn during a lever deflection obtained from the experiments with provoked irregularities revealed that the sensor module is in general very well capable of detecting process irregularities before they have led to major braiding defects like yarn breakage. However, if the worst case test runs are taken as the assessment basis, it becomes apparent that the lead time, in terms of braidable yarn length until final yarn failure, is significantly lower for the PES yarns (13 mm and 47 mm) than for the carbon fibre yarn (510 mm). If a high error detection reliability is required, the number of stationary Hall sensors along the tracks of the bobbin carriers, which acquire the data in a time-discrete manner, has to be increased according to the circumference of the braid and the braiding angle.

Future work will involve the development of additional sensor modules which will be part of the striven, integrated sensor system. Ideas for these modules include the measurement of reaction forces at the braiding ring, the optical observation of the braid formation zone as well as the development of a tension control unit for the rewinding step. Subsequently, real-time capable algorithms which process the data gathered by all sensor modules need to be implemented. Finally, the cost-effectiveness and the economic benefit of the whole system has to be evaluated under near-production conditions.

Acknowledgements

The authors thankfully acknowledge the funding provided by the German Federal Ministry of Education and Research under the scheme “KMU-innovativ: Produktionsforschung” on an integrated sensor system for the monitoring of the braiding process (“Integriertes Sensorsystem zur Überwachung des Flechtprozesses – InSensoFlecht”, funding code: 02P16K553).

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