Investigating the unwinding behavior of technical yarns and development of a new sensor system for the braiding process

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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 and works by contactlessly detecting the positions of the levers of the yarn tensioning units 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 can be calculated. The sensor module was validated by investigating the unwinding behavior of several kinds of technical yarns from bobbins on a stationary test stand which simulates the unwinding process during braiding. 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 which the Hall effect sensors are able to detect. Finally, experiments with the sensors installed into a running braiding machine were conducted. In this near-production environment, the sensor module was capable of identifying irregularities soon enough before major braiding defects evolved.

1. Introduction

The quality of braided textiles from reinforcement fibers 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.

As typical braiding defects, Ebel et al. [1] mention a generally fuzzy braid due to fiber damage, loops in the fabricated preform due to a loss of yarn tension, gaps in the preform as well as yarn breakages. Whereas the fuzzy braid and loops in the preform can be seen as an optical damage, gaps in the preform and yarn breakages have a significant impact on the mechanical performance of the finished part and on machine uptime. They elaborate that these gaps and yarn breakages are commonly caused by a specific effect named fibrous ring. This effect is described as a ring-shaped accumulation of carbon filaments which impedes the yarn from unwinding from the bobbin and consequently increases the yarn tension. It origins primarily from yarn predamage and partly from unsuitable rewinding parameters.

Furthermore, they point 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 fiber as braiding yarns (braiding angle: 45°) and carbon fiber 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 [2] that in a production environment with trained workers, this portion of machine downtime may be lower compared to the investigated research environment. Mierzwa et al. [3] delineate the extent of the deterioration in mechanical properties due to local yarn gaps in braided preforms (braiding angle: 45°) fabricated from T700SC 24k 60E carbon fiber yarns from Toray Industries, Inc. In their test program, they purposefully introduced 4 mm wide gaps into the preforms and infiltrated them using the VAP (Vacuum Assisted Process) and the RTM (Resin Transfer Molding) process. In their subsequent coupon tests of the specimens manufactured by the VAP method, they observed a 36 % reduction in tensile and a 33 % reduction in compressive strength when the gap was oriented perpendicularly to the loading direction. However, they did not observe any significant reduction in strength of the specimens produced by the RTM process. They concluded that – in contrast to the rigid RTM tooling on both sides of the preform – the flexible vacuum bag promoted fiber undulations in the vicinity of the gap which lead to the loss of strength.

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 labor 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.

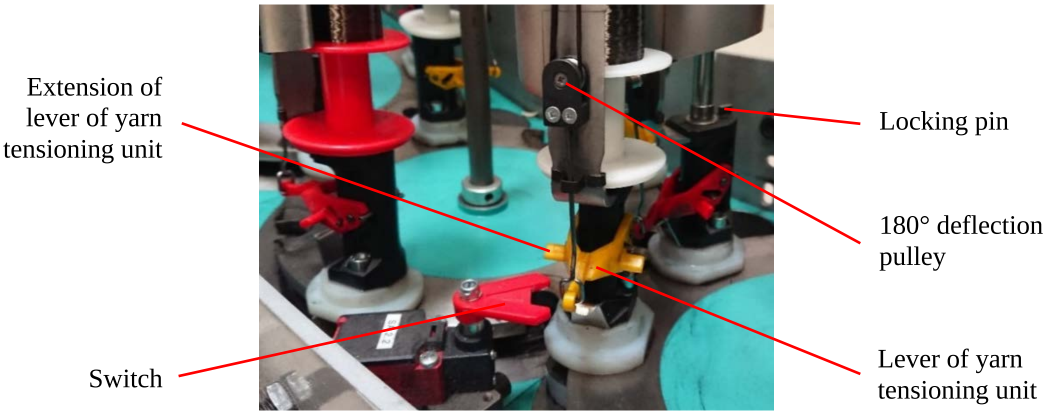

Figure 1. Rudimentary switch jutting into track of bobbin carriers.

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Another bobbin carrier independent system invented by Lenkeit [4] 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 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 may be caused when the yarns touch the skid at high speed. This point is particularly relevant when processing carbon fiber yarns which consist of thin, brittle filaments.

An example for a bobbin carrier dependent sensor system is provided by Braeuner [5]. He 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.

A similar bobbin carrier dependent sensor system was developed by von Reden [6]. He mounted a linear potentiometer as a force sensor, an actively driven bobbin, a control unit, a data transfer unit and an energy supply unit onto a specially constructed bobbin carrier (cf. Figure 2). Moreover, the spindle and its motor which move the yarn deflection element up and down parallelly to the central axis of the bobbin is characteristic for his bobbin carrier. This way, the yarn is always unwound perpendicularly from the bobbin and a defined angle of attack of the yarn tension on the yarn deflection element is ensured. This is needed to obtain precise measurements of the yarn tension from the linear potentiometer.

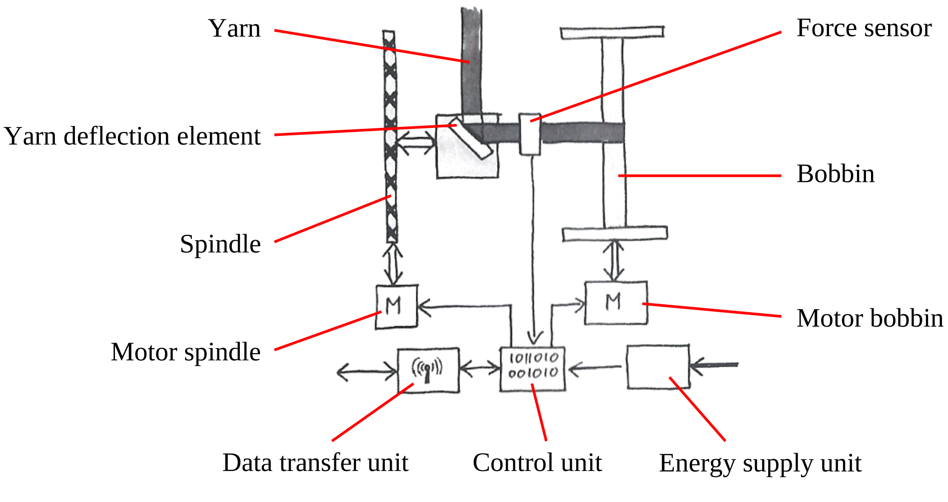

Figure 2. Schematic of the components and their linkages of the electronically controlled bobbin carrier designed by von Reden; image adapted from [6].

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 fiber 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 breakages and consequently to labor intensive error correction. The first sensor module of the system in development with its measurement principle and 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 thread 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 (cf. 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 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 anomalous 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 kJm^{-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 estimated. 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 rotational braiding machine, at least two Hall sensors are required to monitor all braiding yarns of a machine. However, the system can only measure

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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.

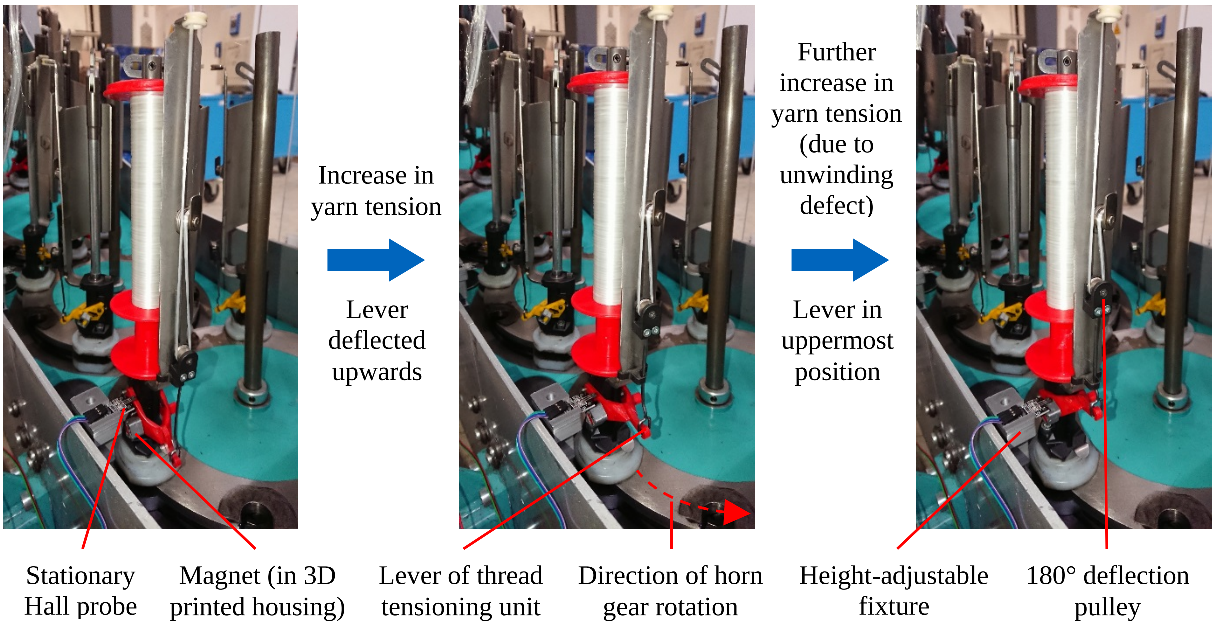

Figure 3. Arrangement of movable bobbin carrier, magnet as well as stationary Hall effect sensor in an RF 1/128-100 braiding machine from Herzog GmbH (all images) and cinematic of lever of yarn tensioning unit with increasing yarn tension (from left to right).

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

To simulate and to closely study the unwinding process during the braiding process, an unwinding test stand is available at the Chair of Carbon Composites at TU Munich. In order to validate the new sensor module, the stationary bobbin carrier of this 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) monofilament 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 fiber yarn of the type Tenax®-E HTS40 F13 12K with a titer of 800 tex. All of the three yarns were tested at unwinding speeds of 40 mms^{-1} and 80 mms^{-1}, 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 fiber yarn were analyzed with a 700 g-spring. Finally, three reference measurements of each configuration to study the behavior of the yarn materials when they are unwound flawlessly as well as five measurements with provoked irregularities were conducted.

4.1. Flawless reference measurements on a stationary test stand

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 simultaneously 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 fiber yarn are shown in Figure 4. The diagram in Figure 4a reveals that the periodic oscillations in yarn tension with the higher frequency – created by cycles of engaging and disengaging the locking pin and determined by the deflection roller based yarn tension measurement device – are well represented by the Hall sensor module. In the diagram in Figure 4b, a superimposed fluctuation in yarn tension with a lower frequency, which was coincidentally discovered, is noticeable. Since the frequency is equivalent to the rotation frequency of the bobbin, this superimposed fluctuation is presumably caused by the central axes of the bobbin and bobbin carrier not being perfectly straight. Even these fine variations in yarn tension are captured by the Hall sensor. Measurements with other materials and unwinding parameters were in line with these findings.

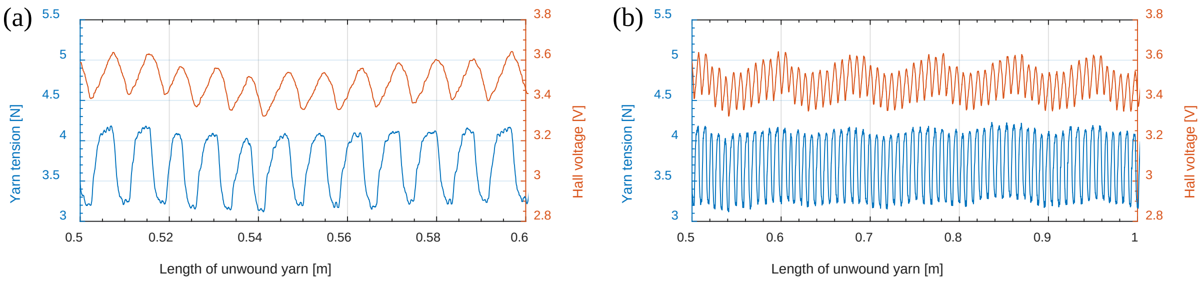

Figure 4. Yarn tension (blue) and Hall voltage (red) obtained from unwinding experiments with a pristine carbon fiber yarn at 40 mms^{-1} unwinding rate and 350 g-spring at different levels of detail; higher level of detail (a), lower level of detail (b).

Apart from this slight superimposed variation in yarn tension, a second, stronger superimposed fluctuation in yarn tension was observed when conducting experiments with the 700 g-spring. To illustrate this, a comparison between measurements obtained from test runs with a 350 g-spring and a 700 g-spring is shown in Figure 5. Whereas the yarn tension remained in a corridor with constant lower and upper bounds of about 3 N and 4.5 N for the 350 g-spring (cf. Figure 5a), especially the upper bound of the yarn tension varied between about 9 N and 16 N for the 700 g-spring (cf. Figure 5b). Matching the measurements with the videos obtained from the SLR camera revealed that the values of the upper bound of the yarn tension depend on the position in longitudinal direction of the bobbin where the yarn is being unwound. Unwinding the yarn from the lower (upper) part of the bobbin lead to a lower (higher) upper bound of the oscillating yarn tension. This is due to the fact that the first yarn deflection element is – in contrast to the one displayed in Figure 2 – fixed on the bobbin carrier that was used. Since there is always a bit of play of the bobbin on the bobbin carrier, the varying angle of attack of the yarn tension on the bobbin causes the bobbin to be lifted from (pushed down towards) the locking pin. This means that the locking pin needs to be retracted less (more) to disengage with the lateral notches in the bobbin. Such behavior was particularly pronounced when the testing the PES multifilament as well as the carbon fiber yarn with the 700 g-spring. When testing all of the materials with the 350 g-spring, this behavior was partly observable and it was not observable when testing the PES monofilament with the 130 g-spring. Since the measurements obtained from the Hall effect sensor showed similar patterns, the authors concluded that this measurement concept was in principle suitable for detecting thread tension anomalies during braiding.

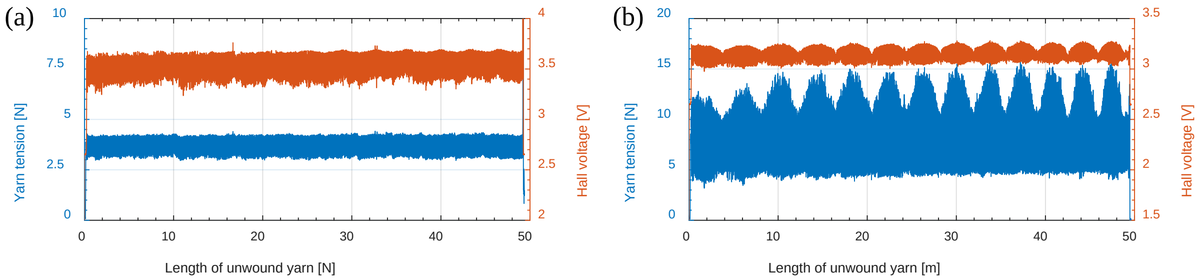

Figure 5. Overviews of measurements of the yarn tension (blue) and Hall voltage (red) of a pristine carbon fiber yarn at 40 mms^{-1} unwinding rate and 350 g-spring (a) as well as 700 g-spring (b).

4.2. Measurements with provoked irregularities on a stationary test stand

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. The carbon fiber yarn was manipulated by predamaging it 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 manipulated by rewinding it 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 manipulated by rewinding it 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 kilometers 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. In the diagram in Figure 6a, an exemplary measurement of an unwinding test conducted with a carbon fiber yarn with a provoked

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fibrous ring is shown. Prominent rises in yarn tension throughout the test run precede the final yarn breakage. The rises in yarn tension are accompanied by comparatively long lever deflections that are detected by the Hall effect sensor. The diagram in Figure 6b shows a representative measurement curve of an unwinding experiment with a manipulated PES multifilament. There are also rises in yarn tension during the experiment observable that precede the final yarn breakage. However, the lever deflections are shorter than the deflections during the experiments with the carbon fiber yarn. In the diagram in Figure 6c, an exemplary measurement of a PES monofilament is depicted. In general, few lever deflections shortly before the yarn broke were observable with this kind of material.

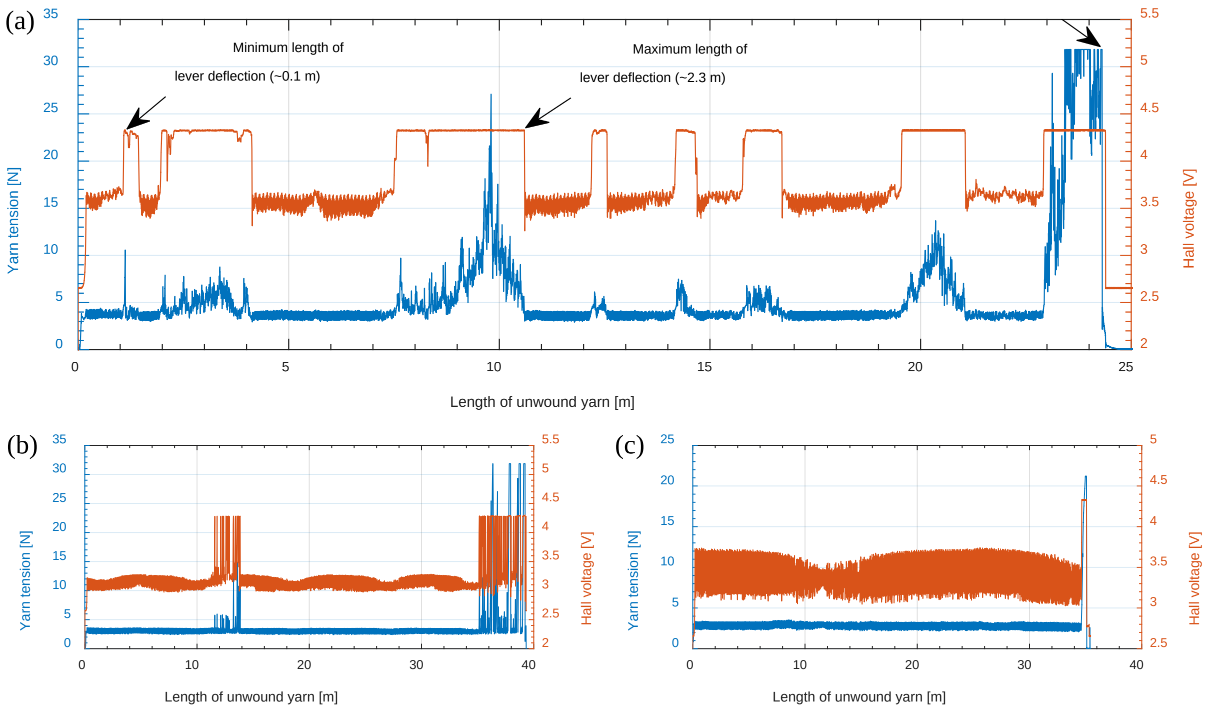

Figure 6. Measurements of the yarn tension (blue) and the Hall voltage (red) during unwinding a manipulated carbon fiber yarn (a), a manipulated PES multifilament yarn (b) and a manipulated PES monofilament (c) at an unwinding rate of 40 mms^{-1} and a 350 g-spring.

The unwound lengths of yarn from the bobbins when the lever was detected in its uppermost position were analyzed for all tests which showed unwinding irregularities. The condensed results of this analysis are depicted in Table 1. The threshold above which the lever was assumed to be in its uppermost position was set to 4.2 V for the data shown in the table. Different thresholds may lead to slightly different results. However, the general findings remain the same. 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 reveals 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 single 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 the carbon fiber yarn and considering typical circumferences and fiber angles of braided carbon composite parts, a single sensor per track is expected to work very well for 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. The lead time in terms of unwound yarn length is already shorter in the case of the PES multifil (237 mm). Due to the fact that typical products made from this material (e.g. shoelaces) also show significantly smaller circumferences, the detection probability of unwinding irregularities may still be characterized as sufficient. However, the detection of loops which entangle during unwinding of the double-folded PES monofil is not fully guaranteed since the lead time was – in the worst case measurement – only 47 mm.

Table 1. Analysis of lever deflections during unwinding tests.

Material		Carbon	PES multifil	PES monofil
Number of specimens [-]		20	20	20
Number of tests with yarn breakages / stepper motor overloads [-]		20	16	20
Mean number of lever deflections per test with unwinding irregularities [-]		5.5	23.9	3.5
Unwound yarn length during single lever deflection [mm]	Min	1	1	2
	Mean	1038	129	522
	Max	4362	1351	6655
Cumulated unwound yarn length during all lever deflections per test [mm]	Min	510	614	47
	Mean	4753	2049	1101
	Max	14058	4363	6691
Overall minimum of unwound yarn length during longest lever deflection per test [mm]		510	237	47

4.3. Test of the sensor module in an operating braiding machine

On the stationary test stand, the measurement principle has shown to theoretically be capable of detecting fibrous rings when processing the carbon fiber yarn. The sensor module was then tested in a running braiding machine to validate its functionality in a near-production environment. For this, 64 bobbin carriers of an RF 1/128-100 braiding machine from Herzog GmbH were equipped with bobbins onto which 100 m of the carbon yarn were wound. For the first test, no bobbin was manipulated. For the second test, one bobbin was manipulated in a way that it already featured a fibrous ring before braiding. Four bobbin carriers from the same track, including the one carrying the manipulated bobbin, were equipped with magnets. One stationary Hall effect sensor was installed and the height of its fixture adjusted in a way that the sensor was able to detect the positions of the levers of the yarn tensioning units of the bobbin carriers when they pass by. A cylindrical mandrel with a diameter of 65 mm and a length of approximately 2 m was then overbraided. The speed of horn gear rotation was set to 60 rpm and the haul-off speed of the mandrel was set to 12 mms^{-1}. This resulted in a braiding angle of approximately 47°. The measurement curve from the first, flawless test is depicted in Figure 7a. In the beginning of the experiment, the braiding yarns are not fully tensed, yet. Due to the fact that there are 32 horn gears in the machine, it takes 16 s for a bobbin carrier to complete one circulation through the braiding machine at the adjusted speed. Since four bobbin carriers from the same track were equipped with magnets, there are peaks in the signal from the Hall effect sensor every 4 s. Also, every fourth peak is induced by the same bobbin carrier. The maximum values of the peaks are around 3 V. These values indicate that the yarn is unwound regularly from the bobbins. By contrast, in the diagram which is shown in Figure 7b, there are two prominent peaks in the Hall voltage with maximum values of more than 4 V at about 32 s and 48 s. These high peak values are caused by the increased yarn tension which is induced by the fibrous ring that was purposefully introduced before braiding. Already observable at second 64 and clearly visible from the regular sequence of small peaks starting at second 80, the yarn that is excessively tensioned by the fibrous ring eventually breaks. This means that the sensor module was capable of detecting an unusual rise in yarn tension well before a yarn breakage occurred.

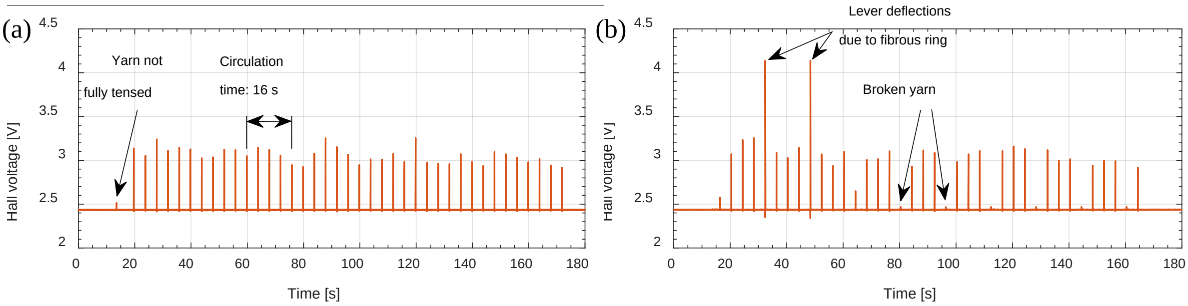

Figure 7. Comparison of measurement curves obtained from a hall sensor implemented into a braiding machine during regular operation (a) and during operation with a provoked fibrous ring (b).

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 estimating the yarn tension of braiding yarns in discrete time intervals. Validation experiments on a stationary test stand with carbon fiber 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 monofil (47 mm) than for PES multifil and the carbon fiber yarn (237 mm and 510 mm, respectively). 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. The sensor system was also tested during operation of an RF 1/128-100 braiding machine from Herzog GmbH. In this a near-production environment, the sensor module was able to detect an anomalous rise in yarn tension caused by a purposefully introduced fibrous ring soon enough before the yarn broke.

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.

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